Simulation of wind-driven ventilation in an urban underground station

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Abstract

Sustainable Energy Management for Underground Stations (Seam4us) is a European research project aimed at developing adaptive control technologies to reduce energy consumption in subway stations. The research work is developed through a pilot subway station, the Passeig de Gracia – Line 3 station, in Barcelona, Spain. The entrances to the subway station are located along Passeig de Gracia, one of Barcelona's main avenues. In this type of location, evaluating the effects of wind in terms of underground ventilation, requires profound investigation. In the perspective of the Seam4us project, wind-driven ventilation must be known a priori in order to evaluate natural ventilation potentials and patterns related to wind-driven ventilation, and to compute wind pressure coefficients used in a synthetic lumped parameter model that is the training model for the control policy. In this perspective, an urban canyon model was built in a commercial CFD simulation environment. Different CFD modeling steps and simulations were faced in order to achieve reliable data, which was then compared with experimental data retrieved from an on-site survey. The results are discussed in the present paper.

1. Introduction

Evaluating the effects of wind, in terms of building ventilation, calls for profound investigation. Factors due to wind forces affecting the ventilation rate inside buildings include average speed, prevailing direction, seasonal and daily variation in speed and direction, and local obstructions such as nearby buildings, hills, trees, and shrubbery (Liddament, 1988).

(Horan et al., 2008) showed that assuming external airflow data on the basis of a single, mean wind speed, and an associated prevailing wind direction, could result in significant variations in ventilation rates, and in comfort conditions when other, external wind conditions prevail. Furthermore, the relationship between wind direction and air change rate proved to be non-linear in many cases.
To model the effects of airflow in buildings, wind speed and direction frequency data are necessary.
Generally, the turbulence or gustiness of approaching wind, and the unsteady character of separated flows, cause the fluctuation of surface pressures. (ASHRAE, 2005) states that although peak pressures are important with regards to structural loads, mean values are more appropriate for computing infiltration and ventilation rates. It considers time-averaged values for pressure, with the shortest averaging period of about 600s (approximately, the shortest time period considered to be a "steady-state" condition when considering atmospheric winds) and the longest 3600s. Instantaneous pressures may vary significantly above and below these averages. Peak pressures even doubled or tripled their mean values.
Furthermore, urban environments have drawbacks in terms of the application of natural ventilation: lower wind speed and higher temperatures due to the effect of urban heat island, noise and pollution (Ghiaus et al., 2006). The meteorological models currently available usually give the wind, temperature, and sky cover on a fictitious surface, usually measured at 10m above ground level, and on a several kilometre grid, approximately. These values need to be changed as a function of the

urban environment (Ghiaus et al., 2003) in order to be used for estimating natural ventilation airflow due to wind pressure and stack effect. An urban canyon is an urban environment artefact similar to a natural canyon. It is characterized by streets cutting through dense blocks of structures - generally heights (Santamouris et al. 1999). Airflow in street canyons has much lower values as compared to undisturbed wind. Lower wind velocity means reduced wind pressure on building facades and less effective cross ventilation. Experimental evaluation of the reduction of airflow rate in single-sided and cross-ventilated buildings in 10 urban canyons in Athens (Geros et al., 1999) showed that airflow rate might be reduced by 90%. Knowledge of the wind speed in urban canyons is a required input for estimating the natural ventilation potential of urban buildings, as well as thermal comfort in open areas. Wind flow inside canyons is driven and determined by the interaction of the flow field above buildings and the uniqueness of local effects such as topography, building geometry and dimensions, streets, traffic, and other local features.

Three approaches can be used to acquire data regarding urban canyon wind flows:

Measurements on site: This process requires months for the acquisition of data using anemometers and important instrument set-ups;

Wind tunnel tests: A slightly faster approach, but also a more expensive one, especially in terms of the construction of the neighbourhood and buildings' physical model ;

Computational Fluid Dynamics (CFD): a faster and cheaper approach, producing much more detailed information but also more "uncertain" data.

While the use of CFD in engineering practice is becoming a well-established procedure in indoor applications, they are used considerably less in outdoor applications; although numerical modeling with CFD is becoming a quite common approach for urban wind simulation. Indeed, CFD models can provide detailed information regarding relevant flow variables in the whole calculation domain ("whole-flow field data"), under well-controlled conditions and without similarity constraints. Furthermore, CFD models can avoid some of the limitations found in other models. Even so, numerical and physical modeling errors need to be assessed by detailed verification and validation studies (Franke et al., 2007).

2. Urban Canyon Model in Seam4us

The development of a new class of energy control systems for underground public environments is one of the main objectives of the EU-funded R&D project called Sustainable Energy Management for Underground Stations (SEAM4US). The project aims at developing a fully featured pilot system, in Barcelona's "Passeig de Gracia" subway station, for the dynamic control of energy consumption, capable of setting up internal environments opportunistically and optimally, based on external environment forecasts, according to energy efficiency, comfort and regulation requirements.

The development of this class of advanced control system requires a robust modeling framework (Giretti et al., 2012) as the models are needed both for being embedded in the control system and for supporting the whole system design, especially the monitoring sensor network.

In this perspective, the model-engineering framework in SEAM4US is hybrid (Ansuini et al., 2012) as it includes different types of models (FEM, Lumped Parameter, and Probabilistic Models) and diverse processes (heat transfer, fluid dynamics, pollutant transport, lighting) at various scales (meteorological weather, local weather, indoor environments).

A very critical point is modelling the effect of meteorological weather conditions inside stations. Every subway station has numerous entrances, thus a local weather station deployed in each of the entrances is economically unsustainable. The idea currently being developed uses a third party weather forecasting service for gathering information pertaining to the climatic conditions within the city, and includes knowledge about local conditions related to a specific urban context as well as the entrances' geometric features, in embedded models. Thus, only one local weather station is deployed in each station (as part of the monitoring system) and used to check the weather model in real-time.

Two types of models are required:
A weather model including the third party weather service data and correlation among the aforementioned data and locally measured data,
A general model of the energetic behaviour of the station building, including the effect of external weather, using a thermal coefficient and a set of specifically computed Wind Pressure Coefficients (Costola et al., 2009).
The development of both the models requires the initial development of an urban canyon model.
This study presents the urban canyon model developed for the SEAM4US pilot station, located in Passeig de Gracia (PdG), Barcelona. Only a very preliminary set of experimental data is available to date, gathered during a two-day environmental survey. These data are used in this study for performing a preliminary calibration of the developed CFD models and for defining a methodology for selecting real-time experimental data to be used in the weather model check.

3. Model development

3.1 Model settings

Accuracy is an important matter of concern when using CFD for modeling urban blocks. Care is required in the geometrical implementation of the model, in grid generation and in selecting proper solution strategies (Franke et al., 2007).
An outdoor urban canyon model was developed. It encompasses the eight city blocks surrounding the station entrances. In order to be used to determine the velocity maps at the station entrances and inside the station, the model also contains the underground environments (Fig. 2).
Critical parameters were determined on the basis of the literature (Franke et al., 2004). Specifically, it emerged that the main decisions to be taken regarded:

- the general modeling approach (what was to be modelled) ;
- the computational domain;
- insertion of the "boundary layer" ;
- roughness of the material;
- geometrical detail level.

Regarding the modeling approach, according to (Franke et al., 2007), the final decision was to model only the volumes of fluid (air) included among the buildings and inside the station. Hence, a domain composed of a single material was inserted in the calculation software. Thus, all other components that really exist were excluded in order to obtain a simple geometry, capable of reducing the computational charges.

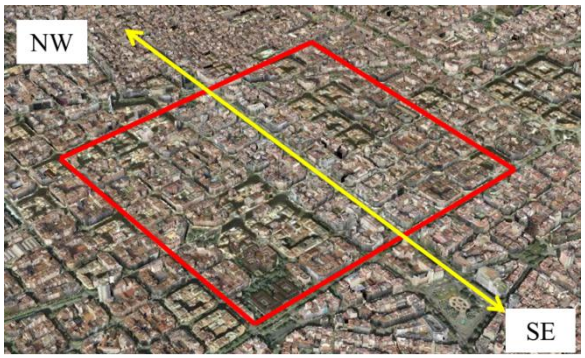

Fig. 1 – Urban Region around PdG modelled

The computational domain consists in a box measuring 2 km in length, 1.5 km in width and 220 m in height, where 20 m was the height of the ground and 200 m that of the air. The PdG underground station has eight entrances. It measures 630 m in length along the homonymous street and measures about 190 m in width in the perpendicular direction. Two different regions are defined in the computational domain (Fig. 1), a central box containing the real obstacles with their geometric shape and with a level of detail characterized by greater precision close to the points of interest, and a less detailed peripheral zone.
The boundary layer has not been included so far, because the width of the computational domain would generate a computationally uncontrollable number of degrees of freedom.
The roughness of the boundary material is considered, however, editing the speed of friction in the conduit. In particular, the B parameter (Comsol, 2011) is set to the value -3. This value was obtained calibrating internal models of the station with other data gathered in the station corridors during the preliminary survey.
Regarding the level of geometrical detail of the

representation, the buildings were considered with clean surfaces and street furniture in the area surrounding the entrances was included (Fig.2).

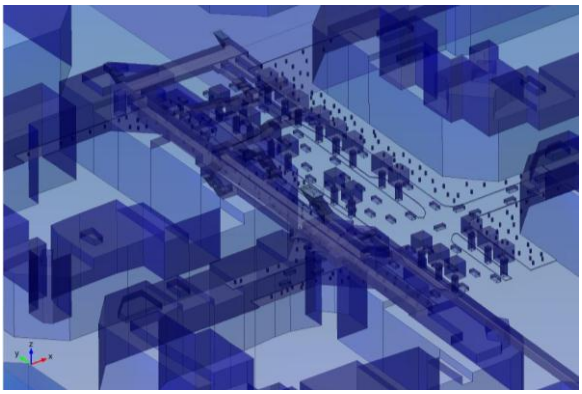

Fig. 2 – Detail of the model in the area surrounding the station entrances

3.2 Boundary Conditions

Four different types of boundary conditions were used (Fig. 3):

Slip condition, imposed on the sky of the computational domain to avoid viscous phenomena on the wall and assuming the continuity of the fluid;

Wall function condition, imposed on the surfaces of the air volume adjacent to a solid;

Inlet condition, applying a velocity profile to the surface of the air box the wind is arriving from;

Outlet condition "Pressure Zero", which considers a pressure profile constant and equal to 0 on the surface, simulating the passage of flow from a tube that represents our computational domain in an undisturbed environment, as occurs in the surface opposite the inlet.

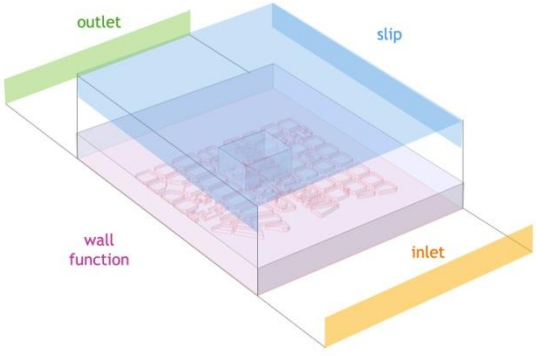

Fig. 3 – Boundary Conditions on different Surfaces

Two types of inlet conditions were considered, each required a different simulation for each model, depending on the velocity profile. Of course, in reality, the wind speed profile along the atmosphere height has a logarithmic trend, but this profile is not fully known, as it will be measured only in one point. This point corresponds to the meteorological weather station. Thus, the definition of the logarithmic profile could include an error related to its trend. On the other hand, the linear profile (according to (Franke, 2004)) can ensure the development of a logarithmic profile due to friction with the ground if used soundly, but the overall effect may be underestimated.

The two profiles considered so far are:

Linear $WS(z) = WS_{Met}$

Logarithmic $WS(z) = WS_{Met}*(z/10)^{0.2}$.

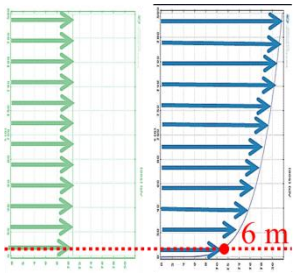

Fig. 4 – Linear and Logarithmic Speed Profile in relation to the experimental WSMet

3.3 Model definition by wind direction

In order to apply the inlet boundary condition efficiently, the surface in which it is applied must be normal to the wind vector direction. Thus, different models were developed for each of the sixteen, main wind directions, resulting in eight different geometrical models (opposite wind directions can use the same geometry).

3.4 Meshing

The results of the computation are strongly dependent on the grid that used to discretize the computational domain. In this case, two different meshes were used for the two different computational domains.

The discretization of the model is obtained by means of a free form mesh grid (normally tetrahedral), which varies in size according to the degree of accuracy to be obtained.

The CFD program used in this study allows two types of meshes: one, based on the general physical

behaviour that does not require a very accurate grid (the default size is then larger), and another, based on the fluid dynamic models' degree of accuracy (the default size is smaller) (Fig. 5). The two subsets include various grid default sizes ranging from an extremely detailed grid for the central region (with dimensions sub-centimetre), while the extreme regions are characterized by a much higher minimum dimension mesh (order of 50 m). In this modeling case, a grid size in the order of 30 meters in the peripheral areas and a centimetric grid size, with fluid-dynamic characteristics in the central region, is deemed necessary. Table 1 gives a summary of the meshing details.

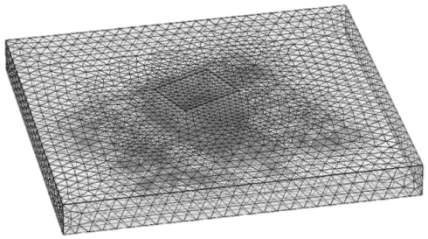

Fig. 5 – Model mesh

	Max elem. size (m)	Min elem. size (m)	Max elem. grow. rate	Resol. of curvature	Resol. of narrow regions
Central	20	0.05	1.5	0.6	0.5
Peripheral	69.5	2	1.2	0.7	0.6

Table 1 – Meshing details

In the post-processing phase, the quality of the mesh was checked, confirming that the variable "wall lift off" δ_w was equal to 11.06 on most of the walls, guaranteeing a good accuracy (Comsol, 2011).

In fact, the wall functions in COMSOL are such that the computational domain is assumed to start at distance δ_w from the wall, which is the distance from the wall where the logarithmic layer would meet the viscous sub-layer if there were no buffer layer in between.

3.5 Model solving

The simulations were carried out by means of COMSOL Multi-physics 4.3, 3D steady state analysis (Comsol, 2012).

The Physical Equations used are those related to the κ-ε Turbulence Model (Wilcox, 1998) in steady Reynolds-averaged Navier-Stokes (RANS) simulation, which is the commonly used method (Yoshie et al., 2007).

4. Experimetnal data

An environmental survey in PdG station was carried out on the 21st and 22nd of March 2012 to retrieve a very preliminary snapshot of the pilot station's environmental behaviour.

A number of different types of data were collected, including local weather data using a weather station (WS3600 LaCrosse Technology) placed close to the EN5 entrance (Fig. 6). The instrument has a resolution of 0.1 m/s for WS and 22.5 deg for WD.

The data was acquired with a 1 minute time step from 9:00 a.m. to 6:00 p.m. during the first day and from 9:00 a.m. to 3:00 p.m. during the second one (Fig. 7).

Fig. 6 – Local Weather Station during the survey

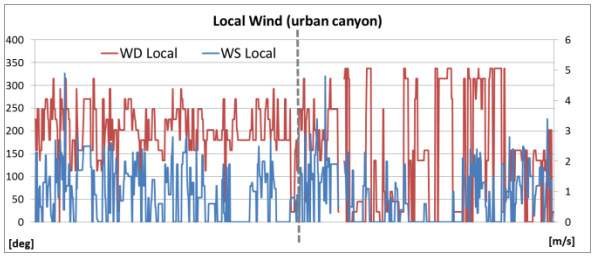

Fig. 7 – Original data acquired by the Local Weather Station during the survey.

4.1 Calibration approach

For the calibration of the weather models, the SEAM4US project uses two types of Wind Measurement (Fig. 8):

Local Wind data, similar to that retrieved during the preliminary survey, gathered from the Weather Station placed in the entrance EN5;

Meteorological Wind data retrieved by a third party weather service. The services considered so far, for the city of Barcelona, use mainly data gathered by the Barcelona El Prat Airport weather station, situated at an altitude of 6m, free field.

This data was also used for the preliminary calibration.

Fig. 8 – Diagram of the relation between Meteorological and Local Wind

4.2 Analysis of Meteorological Wind Data

Meteorological wind data, corresponding to the Local Weather Station's measurement time-period, was collected. The weather forecast services considered provide 30 minute averaged data, thus, 19 records for the first day, and 17 records for the second. Their distribution in terms of WD and WS are shown in Figure 9.

4.3 Definition of the CFD model set

The data available was analysed and 22 boundary conditions were identified on the basis of the winds occurring. The related models were developed and simulated.

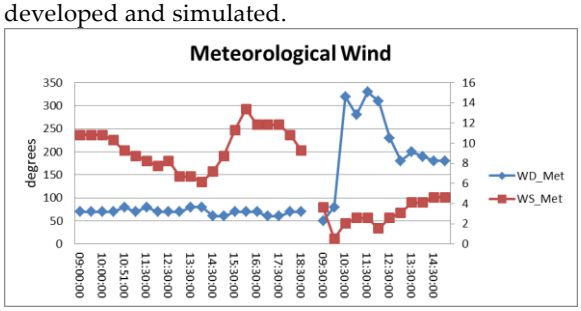

Fig. 9 – Data about the Meteorological Wind related to the survey period

4.4 Detailed analysis of local wind data

The critical part of the calibration process is then the analysis of local wind data. Weather stations, such as the one used in the survey, have a rather low accuracy: ±10% (AmbientWeather, 2012) that can increase to ±30% for WS < 1 m/s (Rossi, 2003). Furthermore, in terms of WD, they give a result even if WS=0 (no wind).

Hence, in the perspective of real-time checking/calibration, the definition of a protocol for defining data reliability is critical.

As the data are averaged for each half hour, 30 measures are expected for each interval. The analysis used in this study aims at defining the reliability of measures, depending on three parameters:

Validity: that is, computing the number of measures that are valid and correspondent to a wind (WS>0). The interval set is defined valid if at least 10 measures are valid;

Reliability: that is, computing the number of measures corresponding to WS>1 m/s. The interval set is defined reliable if the majority of the valid measures are also reliable;

Direction Prevalence: that is, computing the number of occurrences of each WD between the valid measures. If the most frequent WD, in terms of occurrence, has a number of measures greater than one-third the number of valid measures, and at least double of the number of the second WD cases, in terms of occurrences, it can be considered a prevalent direction (Fig. 10).

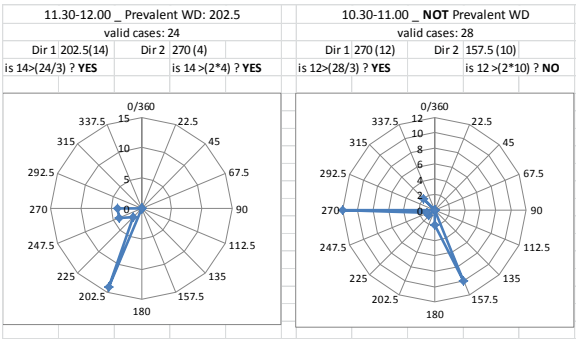

Fig. 10 – Example about the identification of Prevalent WD in a half hour interval

Setting the reliability threshold to 1 m/s is related to (Rossi, 2003) and can be considered plausible for our case given that its effect inside the station is not

very relevant when the outdoor wind speed is low.
Based on these criteria, only reliable measures were considered, hence, 17 half-hour intervals from the survey data. For each interval, average WD_{Loc} and WS_{Loc} were computed.
WD_{Loc} was computed as the direction occurrence weighted average of the valid WD measures, paying particular attention to accounting properly the cases where the measures were around the 0/360 angle.
WS_{Loc} was computed differently depending on whether or not there was a single, prevailing wind direction: if a prevalent direction existed, the average, prevalent direction, WS was used. However, if a prevalent wind direction did not exist, the weighted average of all the average WS for each direction was used.

5. Results and discussion

5.1 Simulation Results

The whole CDF model set identified was developed and simulated. A line of plotting points was defined in each model, centred on the actual position of the Weather Station during the survey (Fig. 11).

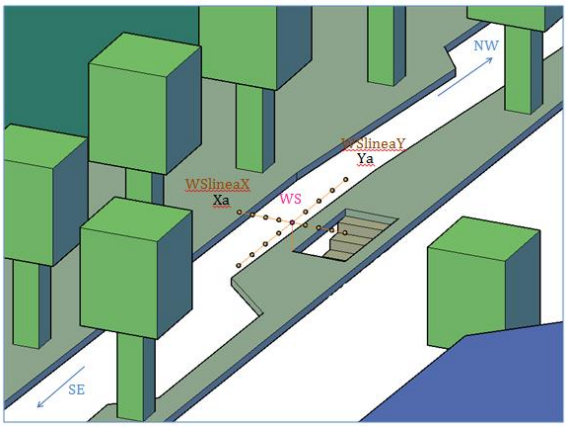

Fig. 11 – Plot points around the weather station

Table 2 reports the simulation results related to the reliable data of Local Wind, in both inlet conditions cases: linear (lin) and logarithmic (log) speed profile.
The analysis of the simulation performance was performed in terms of WD and WS.

In terms of WD, the results are very good as the mean errors obtained are ±27.98 (lin) and ± 27.30 (log). Recalling that the weather station precision was ±22.5 degrees, the results appropriateness is confirmed. In percentage terms, the relative errors are ±14.9% and ±14.3%, which, considered in reference to 360 degrees, are ±7.8% and ± 7.6%.
In terms of WS, the mean errors obtained are ±0.62 m/s (lin) and ± 0.41 m/s (log), corresponding to relative percentage errors of 36.8% and 26.8%.

time	WD_{S_Lin}	WS_{S_Lin}	WD_{S_Lo}	WS_{S_Log}
9.30-10.00	216.58	0.92	221.54	1.90
10.00-10.30	216.31	0.82	221.13	1.69
10.30-11.00	216.31	0.82	221.13	1.69
11.30-12.00	215.40	0.60	219.58	1.20
12.00-12.30	215.40	0.60	219.58	1.20
12.30-13.00	215.40	0.60	219.58	1.20
13.00-13.30	185.00	0.84	187.88	1.10
13.30-14.00	185.00	0.84	187.88	1.10
14.30-15.00	221.23	0.96	223.21	1.66
15.30-16.00	215.81	0.95	221.54	2.08
16.00-16.30	215.81	0.95	221.54	2.08
17.00-17.30	225.89	1.26	226.61	2.05
17.30-18.00	216.58	0.92	221.54	1.90
12.30-13.00	187.96	0.50	187.85	0.64
13.30-14.00	145.22	0.87	136.80	1.12
14.00-14.30	187.96	0.50	187.85	0.64
14.30-15.00	187.96	0.50	187.85	0.64

Table 2 – Simulation Results

5.2 Discussion

Figures 12-15 support a detailed analysis of the results.
Figure 12 represents WD and WS with the results ordered by WD_{Met}.
It emerges that the cases related to directions 80, 180 and 190 have recurrent problems, in terms of both WS and WD. In particular, the WS graph (Fig. 12b) shows that this problem is not related to the inlet condition and it should be related to the model. This behaviour has a physical explanation, as these directions are the most oblique to the city

block grids (and to the canyon) as showed in Figure 13.

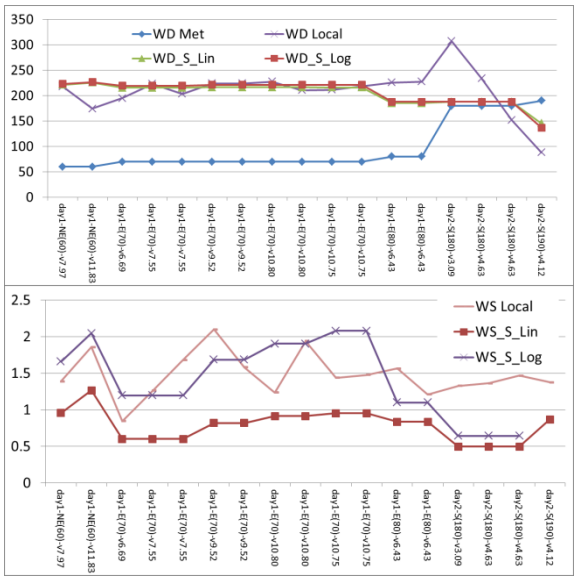

Fig. 12 – Simulation and Experimental Results ordered by WDMet:WD (a) and WS (b)

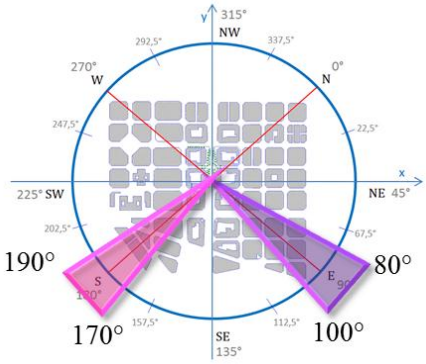

Fig. 13 – Superposition of cardinal axis to the urban canyon schema and identification of the oblique WD.

Furthermore, especially in regards to the south (180), there are two building blocks situated exactly perpendicular to this direction that could be causing the problems.

Solving the aforementioned problem is not easy, but taking it into consideration is very relevant in the perspective of defining a real-time checking/calibration protocol.

Figure 14 represents WD and WS with the results ordered by WS_{Met}. It emerges that the WD gap between simulation and measurement clearly decreases while WS_{Met} increases.

In terms of WS gap, it emerges that the worst cases are the cases related to WD_{Met} =180, as these are not only "oblique", but they are also the ones with the lowest wind speed.

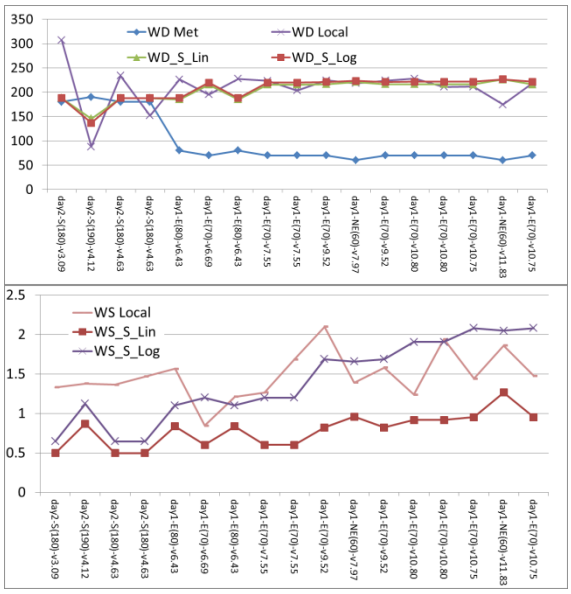

Fig. 14 – Simulation and Experimental Results ordered by WSMet:WD (a) and WS (b)

Finally, Figure 15 shows the relative percentage error for WS in the two cases, with simulations ordered by WD_{Met}. It clearly shows that the two simulation sets' trend is similar, but "shifted", except for the "oblique" cases where they tend to overlap.

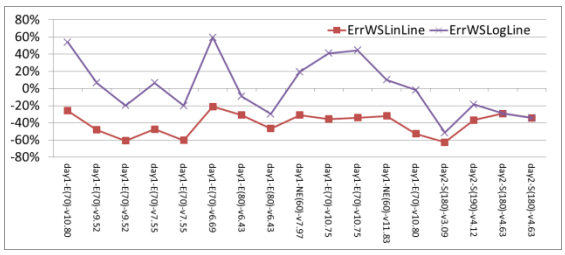

Fig. 15 – Relative Percentage Error for WS

"Shifting" is an expected behaviour because, as previously stated, the two inlet conditions relate to different average WS_{Met} on the inlet surfaces. In fact, the two profiles have the same value in the point where height is 6m (altitude of the weather station at the airport) but the logarithmic profile then increases, resulting in a higher average value (Fig. 4). So far, the simulation using a logarithmic profile obtains better results. However, the existence of a "shifting" between linear and logarithmic model results also confirms that, in terms of WS, a further calibration might be required for both the cases. This calibration will be performed when a set of - statistically speaking -

more reliable experimental data is available.
It also emerges that there is still a "fluctuation" of the model's performance in terms of WS. In our opinion, this could be related to two main aspects.
The first is "structural" in the process, and it is related to the action of "averaging" the wind. Averaging the wind speed, and defining the prevalent wind direction for both the two locations, is a very critical step in this process. So far, two different subjects conduct this step autonomously (the airport weather service and the authors) for two different sets of data. This procedure will be the same during the real-time phase, although, a deeper investigation regarding the averaging interval length could be useful. The 30-minute length chosen so far is related to the availability of real-time data from the meteorological weather services. The averaging interval could be modified to 10 minutes, if more detailed data from some weather service is made available.
The second aspect is the possible inaccuracy of some measurements in both the two weather stations (airport and canyon) during the survey. So far, the preliminary calibration is based on 17 cases, meaning possible "wrong" measures (not easy to be identified, especially if they are related to the weather station at the airport, not directly managed by the authors) highly affect overall performance. This aspect will be investigated further using statistical correlations when more experimental data is available from the local weather station. Thus, the weight of possible "anomalous" cases will be reduced statistically.

6. Conclusion

This paper presents the development and preliminary calibration of a CFD urban canyon model used in the EU funded project SEAM4US. The model aims at representing the relation between Meteorological Wind and local winds near subway station entrances; in this case, the pilot case used is the Passeig de Gracia subway station in Barcelona.
The preliminary calibration is based on a small experimental data set, thus the results will have to be updated with a larger set of data. However, the preliminary results showed a very good convergence in terms of WD, with an average error of 27.30 deg, close to the precision of the instrument 22.5 deg. In terms of WS, the model would benefit from a further calibration (average error 0.41 m/s), which will be performed once more experimental data is available.
Furthermore, the paper discusses the data in the perspective of defining a protocol for the real-time comparison of experimental data concerning Meteorological and Local Wind, and simulation results, as this operation will have to be performed by the SEAM4US Control System.

7. Nomenclature

Symbols

WS	Wind Speed (m/s)
WD	Wind Direction (degree)

Subscripts/Superscripts

Loc	Local (in the urban canyon weather station)
Met	Meteorological (in the airport weather station)
S_Lin	Simulated/Linear Inlet Condition
S_Log	Simulated/Logarithmic Inlet Condition

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