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Evaluation of ventilation loads in buildings energy modelling at urban scale

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***Abstract*— Generally, the models for evaluating the energy performance of buildings have a ventilation thermal load that depends on the type of building and its occupancy rate. The models apply a constant rate of air changes and therefore the ventilation load depends on this value and on the temperature gradient between internal and external environments. In this work, a single zone air flow model is presented to modify monthly the air changes according to the climatic data, the air permeability, shape and orientation of the building and the urban morphology. The results of this work, show how the air change rates vary with the building floor and with the wind direction and velocity. For both case studies, the air changes per hours vary monthly with minimum values in wintertime and with monthly differences of 41%. Of course, if the building is not well exposed and there is no wind, the air infiltrations are not sufficient to ensure good air quality conditions and it will be necessary to open the windows. In these first two case-studies, a very simple single zone evaluation of air flow rate by natural ventilation improved the existing energy performance place-based model. The results of this work encourage the application of this model at district-urban scale, taking into account the characteristics of each single building and its surroundings.**

Keywords—wind-driven ventilation, single zone air flow model, buildings, energy performance model, urban scale.

I. Introduction

The development of countries is increasingly linked to the availability of energy throughout the territory, guaranteeing the continuity of supply, even in the event of catastrophic events, and above all accessibility not only physical but also economic for all citizens. These conditions can be achieved by self-producing the energy required, perhaps with low-emission systems such as technologies that exploit locally available renewable sources. In this context, the planning of energy supply and demand becomes very important, and the scale of this evaluation can only be territorial. In fact, if we want to exploit renewable sources, we must remember the nature of these sources is dispersed and discontinuous. This implies a significant use of the territory, the use of storage systems and an optimization of the energy mix in order to continuously exploit different energy sources.

In recent years, place-based energy planning has become a very important tool for managing energy supply and demand in a sustainable and optimized way [1]. The models for energy demand that are most effective are the engineering models that allow, by modifying some variables, to verify different and future scenarios. The work here presented introduces an improvement to a place-based model for assessing the energy demand/consumption of residential buildings for space heating on a territorial scale, evaluating the variation of ventilation load as a function of climate conditions, building permeability and the surrounding context. In this work, the methodology is applied at two buildings with different orientations knowing their consumptions but, in future works, will be applied at urban scale.

II. Material and Methods

This paragraph reports the databases and the methodology adopted in this work, starting from previous research.

A. Databases of buildings at urban scale

The aim of this work is to find a good assessment to improve the ventilation load in the energy balance model of buildings at urban scale [2, 3]. Therefore, a place-based assessment was developed using the existing databases for spatial planning and the geometrical and typological characteristics of buildings were evaluated by the technical map of the city of Turin (i.e., BDTRE:2019 available at http://www.geoportale.piemonte.it/). Given the position of the analysed district in the City of Turin, the hourly climate data were downloaded from the LinvingLAB@polito.it (at http://smartgreenbuilding.polito.it/monitoraggio/esterno.asp).

B. Buildings' energy modelling at urban scale

The energy balance of buildings at urban-districts-neighbourhoods scale was developed starting from the heat flow equations at buildings scale described by the Standards on energy performance of buildings:

- EN ISO 13790:2008 and the Italian UNI/TS 11300s for the monthly quasi-steady state method
- EN ISO 52016-1:2017 and EN ISO 52017-1:2017 for the hourly method.

The energy balance equations were adapted to the information available at urban scale of the buildings and built context. This work led respectively to monthly (Eq.1) [2] and hourly (Eq.2) [3] models for the evaluation of energy power releases for space heating of buildings that can be applied to a building, a district, or a city:

$$\emptyset_{H,nd} = (\emptyset_T + \emptyset_V) - \eta_{H,gn} \cdot (\emptyset_I + \emptyset_S) \qquad (1)$$

$$C \cdot \frac{dT}{dt} = \emptyset_S + \emptyset_I + \emptyset_{H,nd} - (\emptyset_T + \emptyset_V) \qquad (2)$$

$$\emptyset_V = \rho_a \cdot c_a \cdot \frac{ach \cdot Vol_a}{3600} \cdot (T_{ai} - T_{ae}) \qquad (3)$$

where the heat flow rate for the space heating $\emptyset_{H,nd}$ can be calculated knowing: the heat flow rates lost by transmission ($\emptyset_T$) and ventilation ($\emptyset_V$), and achieved by solar gains ($\emptyset_S$) and internal heat sources ($\emptyset_I$); and T-T_{ai}-T_{ae} temperatures of building, inside air and outside air, C heat capacity, t time, ρ_a-c_a-Vol_a density, specific heat and volume of inside air, and ach is the number of air changes per hour.

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These models had a simplification on the ventilation heat flow ϕ_V with constant ach depending only by the energy efficiency level of buildings with 0.5 air changes per hour (ach) for old windows and 0.3 ach for new ones.

In the next paragraph a methodology is proposed that allows the ach values to be varied monthly according to the speed and direction of wind but also according to the types of openings and urban context. Previous works [4, 5, 6], showed that the air changes, which can be obtained through air infiltrations, can be evaluated knowing climatic conditions, characteristics of buildings (e.g., permeability and building form) and the type of built context.

C. *The evaluation of ventilation load*

In this work, the monthly variation of the ventilation load inside the building considers only the airflow rate due to the wind driven effect of natural ventilation (NV). To assess the airflow rate for infiltration caused by the NV wind driven effect, the pressure coefficients C_p on windward and leeward building façades have been calculated to determine the pressure variations, according to the monthly wind speed and direction. The methodology has been applied to buildings represented with a single zone air flow model for each floor, assuming cross natural ventilation and symmetrical openings (typology and dimension) on the two opposite facades. No internal partitions and connections (e.g., stairwells) have been considered: each floor is a separate and independent air flow zone, as it is schematized in Figure 1.

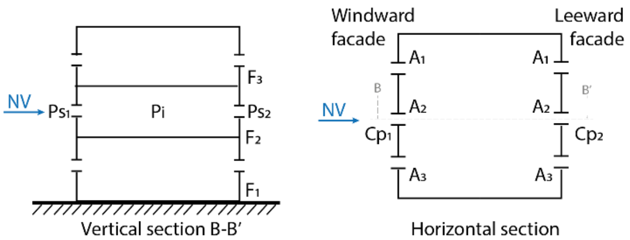

Fig. 1. Sections of single zone air flow model for each floor of buildings.

The methodology applied in this study for the evaluation of the ventilation loads at building scale is synthetized in Figure 2. In the following paragraphs each part will be described in detail.

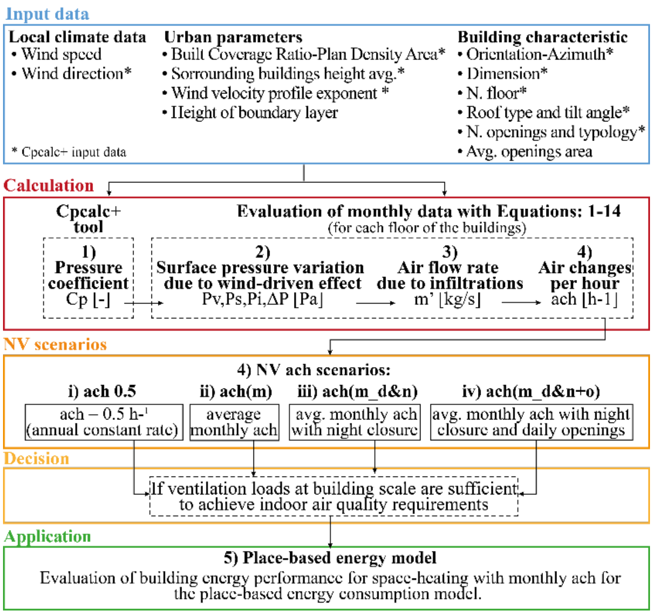

Fig. 2. Scheme of the applied methodology.

A. *Input data*

<u>Climatic data</u>. The monthly prevailing wind direction (WindDir, °) and wind speed (Vzws, m/s) from the nearest weather station (ws) whose location and height (Zws) from the ground are known.

<u>Urban scale</u>. Two urban parameters are needed in order to determine the pressure coefficient at building scale: the Building Coverage Ratio (BCR, m^2/m^2) and the height of surrounding building (H_{sb}, meters). In this work, both parameters have been previously calculated [2] at the census section level, using available data of technical maps using GIS tools. The building density is useful also to determine two specific urban-climatic parameters that influence wind velocity at local level: wind velocity profile exponent (υ,-) and height of the boundary layer (δ, m), determined by literature according to the terrain roughness type [7].

<u>Building scale</u>. The building orientation, dimensions (length, height and width, m) and the number of floors come from the municipal technical maps; the net volume (Vol, m^3) and the total area of openings ($A_{opening}$, m^2) have been determined in previous works [2,3]. The total area of openings has been calculated as the 1/8 of the net floor area (Italian Decree July 5th, 1975: hygiene standard on the aero-illuminant ratio) and it has been distributed on exposed vertical façades of the building identifying the window-to-wall ratio. Knowing the total number of openings on each façade and assuming all openings to be equal on dimensions and typology, the area of the openings has been determined for each floor.

B. *Monthly average wind speed and direction of the weather station*

In this work, the climatic data from the weather station were available at hourly time scale. The evaluation of the ventilation loads variation was conducted monthly. The wind direction data are expressed in degrees (0°-360°); the convention of 0° at North, the clock-wize sense and eight sectors for wind direction (Figure 3) are used [8.]. To determine the monthly average wind sector, the prevailing frequency (%) for each wind direction (WindDir) was calculated monthly. The incidence angle for each wind sector was associated with the average monthly *WindDir* angle with the average monthly wind speed value (Vzws). Figure 3 shows an example of the assessment of the prevailing sector and the wind speed for the December 2014.

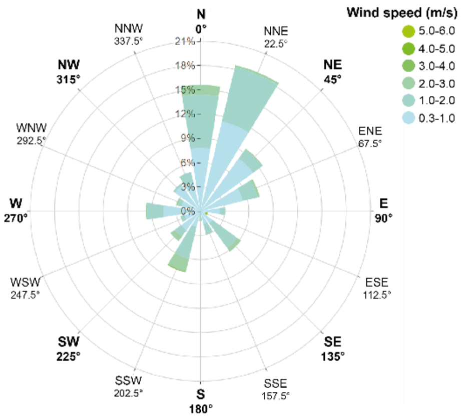

Fig. 3. Monthly prevailing wind direction and wind speed on December 2014 in Turin; concentric circles indicate the wind speed frequency (%).

C. *Wind speed correction*

As reported in literature [9], the wind speed from the weather station (Vzws) has been corrected considering the angle of wind incidence on the windward facades, and the characteristics of the environmental context of both the building and the weather station context. For each monthly prevailing wind direction calculated at point B, the angle of incidence (θ) between the wind direction angle (DirV) and the azimuth of the building (Az) has been determined according to the scheme in Figure 4.

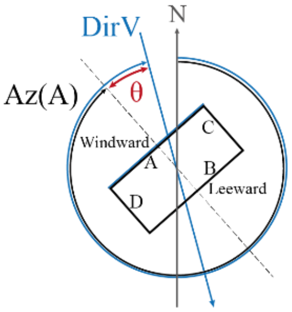

Fig. 4. Definition of the wind incident angle (θ) on the windward façade A, according to the azimuth of the building (Az_A) and wind direction (DirV).

DirV corresponds to the prevailing wind direction, measured clockwise from the north axis to the wind-tail; in this work it coincides with WindDir, measured by the weather station. Az is measured from the north axis and the perpendicular to the longitudinal windward façade; consequently, for each month the angle Az of the resulting windward facade is determined considering the orientation of the building and the wind direction. The monthly average speed data corrected (Vzws_corr) is calculated multiplying the wind speed from reference station (Vzws) by the cosine of the angle of incidence (θ), according to Equation 4 therefore considering only the normal component of incident wind on the façade:

$$V_{zws\_corr} = V_{zws} \cdot \cos(\theta). \qquad (4)$$

The wind speed must be corrected also considering other features to be determined at urban and building scale: i) the environmental context in which the building and the reference station are located, and ii) the elevation of the building openings at each floor and the height of the reference weather station. The wind velocity profile exponent (υ) and the height of the boundary layer (δ) of the environmental context influence the wind velocity; they should be determined both for the case study building and the weather station, knowing their geographical position and the building density of the surrounding environment. The values shown in Table I have been defined in literature [7] and they refer to the terrain roughness types of environmental contexts, according to the building density and the characteristic of the surrounding environment.

TABLE I. HEIGHT OF THE BOUNDARY LAYER AND WIND VELOCITY PROFILE EXPONENT FOR DIFFERENT TERRAIN ROUGHNESSES TYPES.

Terrain roughness type	***δ* [m]**	***υ* [-]**
Level surface, surfaces of water basins, grass land	250	0.10
Flat open country with few, very small, and scattered obstructions	280	0.14
Rolling or level surfaces broken by numerous obstruction	300	0.22
Heterogeneous surface with obstacles larger than one story	330	0.28
Low density suburban areas	390	0.34
Medium-high density urban areas	450	0.40
Very high density city areas	510	0.45

The monthly average speed V_H at the height (Z) of the considered element (n) is determined by Equation 5 [10],

$$V_{H(Zn)} = V_{zws\_corr} \cdot \left(\frac{\delta_{ws}}{Z_{ws}}\right)^{\upsilon_{ws}} \cdot \left(\frac{\delta_{Zn}}{Z_n}\right)^{\upsilon_{zn}} \qquad (5)$$

where Z_{ws} and Z_n are respectively the height of the weather station (ws) and the height of each of the n floors of the building, measured in the barycentre of the opening. In this study, each floor of the building is considered separately and equipped with openings of equal size and position, so the result will be a monthly average wind speed V_H for each of the *n* floors of the building at its height Z_n.

From now on, all the equations described in the next paragraphs will be repeated for each floor, for each facade of the building and for each month of the heating season.

D. *Wind pressure coefficient Cp*

To assess the distribution of wind pressure on a building's envelope, here generated only by the wind driven effect of NV, the majority of the multizone air infiltration models deal with the dimensionless pressure coefficient Cp [11]. It is defined as the ratio between the surface dynamic pressure at a certain height and the one in the undisturbed flow pattern measured at a reference height. At a point on the building façade k (x,y,z), the pressure coefficient Cp for a given wind direction can be calculated by:

$$Cp_k = \frac{P_k - P_{0(z)}}{P_{dyn}(z_{ref})} \qquad (6)$$

where P_k and $P_{0(z)}$ are respectively the surface pressure and the reference static pressure at the height *z* and P_{dyn} the reference dynamic pressure at height z_{ref}, determined by:

$$P_{dyn}(z_{ref}) = \frac{1}{2} \cdot \rho \cdot V_{zref}^2 \qquad (7)$$

with the air density ρ and the wind speed V measured at the reference height z_{ref}.

In this work, the Cpcalc+ tool [12] has been used to determine the pressure coefficient Cp. Developed for the COMIS program by the International Energy Agency [13], it consists of an algorithm able to take into account the context parameters, meteorological and environmental conditions of the site and the geometrical characteristic of the building. Most of the input data of Cpcalc+ have already been determined for carrying out the methodology presented in this work, also highlighted in the scheme in Figure 2: i) climate parameters (wind direction), ii) urban parameter (wind velocity profile exponent, average height of the surrounding building and Plan Area Density-PAD), iii) building geometry (dimension, roof type and tilt angle), building orientation (azimuth of the building) and façade elements positioning.

In particular, the PAD corresponds to the ratio between the *built area* [m^2] and the *total parcel area* [m^2]; the *built area* considers the number of floors of each building, unlike the BCR parameter that only considers the surface occupied on the footprint of each building. The façade element positioning must be determined in the barycentre of each opening on each façade, indicating its coordinate x (respect to the façade length) and z (respect to the façade height).

E. *Surface pressure, air flow rate and ach*

As shown in Figure 1, each floor of the two case study buildings is intended as a single air flow zone with an equal number n of openings located on each of the two opposite facades. To evaluate the surface pressure on building facades, it is assumed that the wind velocity (and direction) is the only phenomenon affecting the natural cross-ventilation of the buildings; neither temperature and humidity gradient between indoor and outdoor air influence the air changes per hour.

As previously described in [14], the presented methodology applies a lumped parameter model of air flow, in which intends to uniformly distribute the characteristics of the air inside the building (e.g. internal air pressure and temperature). The pressure difference Ps generated by the wind-driven effect on each of the two opposite façade is defined by:

$$P_S\,[Pa] = P_V \cdot C_p \qquad (8)$$

where P_v is the dynamic pressure due to the wind flow according to Equation 9 and C_p is the pressure coefficient determined with the Cpcalc+ tool for each opening at each floor on each windward and leeward façade. The overpressure P_v generated by the wind on building façade is determined by:

$$P_V\,[Pa] = \frac{1}{2} \cdot \rho \cdot V_H \qquad (9)$$

where V_H represents the wind velocity at the height of the analysed opening.

Assuming static conditions inside each cross ventilated zone, the conservation of the mass can be applied and the mass balance of air inside any zone (i.e., floor) equals to zero. Therefore, the balance between surface pressure variation Δ_{P1} and Δ_{P2} is expressed by Equations 10 and 11:

$$m'_1 + m'_2 = 0 \qquad (10)$$

$$\Delta_{P1} + \Delta_{P2} = 0 \qquad (11)$$

where Δ_{P1} is the difference between the outdoor pressure P_{s1} on the windward facade and the indoor pressure P_i and Δ_{P2} is the difference between the outdoor pressure P_{s2} on the leeward facade and the indoor pressure P_i, as schematized in Figure 1. Consequently, it is possible to determine the indoor pressure P_i :

$$P_i\,[Pa] = \frac{\rho \cdot (V_H)^2}{24} \cdot (C_{p1} + C_{p2}). \qquad (12)$$

The mass flow rate *m'* [kg/s] is determined as a function of the characteristic of the opening's leakage (dimension and typology) and pressure variation:

$$m'[\frac{kg}{s}] = C_d \cdot \rho \cdot (A_l \cdot A_{floor}) \cdot \sqrt{\frac{2\Delta P}{\rho}} \qquad (13)$$

where: A_l is the normalized leakage area for exterior walls, A_{floor} is the net floor area and C_d the relative discharge coefficient. In this work, all openings are external windows with double shutter casement: the Cd is equal to 0.65, and the A_l 12 cm^2/m^2 (very leaky exterior wall), as reported in [15].

Knowing the monthly mass flow rate *m'* and the air volume inside the building (*Vol*), for each single zone (floor) (analysed separately), it is possible to determine the monthly rate of air change per hour (ach):

$$ach\left[\frac{1}{h}\right] = \frac{m' \cdot 3600}{\rho \cdot Vol_{floor}} \qquad (14)$$

where Vol_{floor} was calculated dividing the air volume of the building by the number of floors.

F. Hypothesis of ach in the energy building model

To evaluate the effect of the monthly variation of the air exchange rate ach on energy consumption for space-heating, different hypotheses of ach were simulated for the two case studies using the building performance energy models [2, 3] and then results were compared with energy consumption data for the heating season 2013-14. The procedure described in paragraph E was applied by calculating the monthly achs by infiltrations and then comparing the results of different scenarios with the one with ach equal to 0.5 h^{-1}:

- *ach(m)* - average monthly ach: determined by procedure at paragraph E, considering a constant discharge coefficient of Cd=0.65;
- *ach(m_d&n)* - average monthly achs with night closure; in this scenario it is supposed an extra closure during night-time: daily and nighttime discharge coefficients Cd were applied, respectively 0.65 and 0.55 to consider shutters;
- *ach(m_d&n+o)* - average monthly achs with night closure and with three windows openings during the day: in this scenario, in addition to the conditions described in the previous scenario, it is supposed to open all windows three times a day for 15 minutes (at 7 a.m., 2 p.m. and 9 p.m.).

III. The Case Study in the City of Turin

The building case-studies are in a district in the centre of the city of Turin, in the North-West of Italy. Depending on the annual local Heating Degree Days (HDD), Turin is located in the climatic zone E (2100<HDD<3000 °C) with a heating season from October 15th to April 15th. Figure 5 shows the residential buildings in the selected neighbourhood of *Crocetta* district located near the weather station of Politecnico di Torino. Two buildings (i.e., ID 23534 and ID 23582) representative of the urban building stock with two typical orientations for the city of Turin have been selected. In fact, the 33.1% of all buildings in Turin is NE-SW oriented with an inclination angle of 30° (±5°) from the North and the 34.4% is NW-SE oriented with an inclination angle of -60° (±5°) from the North [16]. Furthermore, the measured space-heating energy consumption for the heating season 2013-14 is known for both buildings, as it is possible to compare results of the energy performance model to real consumption data.

Fig. 5. The two case-study buildings: ID23534 (in blue) and ID23582 (in green) in a neiborhood of Crocetta district, in the city center of Turin.

At urban scale, these two buildings refer to the similar census sections, for which the urban parameters have been calculate in previous work [2]; so, the urban parameters about building density at district level and the related climatic coefficients for natural ventilation are the same for both selected buildings, as shown in Table II.

TABLE II. CHARACTERISTIC OF CROCETTA DISTRICT

Urban scale input data				
Urban parameter			*Climatic coefficient*	
Built Coverage Ratio (BCR)	**Plan Area Density (PAD)**	**Surrounding buildings height**	**Height of boundary layer (δ)**	**Wind velocity profile exponent (υ)**
[m²/m²]	**[m²/m²]**	**[m]**	**[m]**	**[-]**
0.38	7.78	25	450	0.4

At building scale, both buildings present a double slope roof with a tilt angle of 15-20°, while the main differences between the two buildings, influencing the natural ventilation, are related to their orientation, dimensions, and openings, as reported in Table III.

TABLE III. CHARACTERISTICS OF THE CASE STUDIES

Building input data	*ID 23534*	*ID23582*
Construction period	1916-1945	1946-1960
Orientation	NE-SW	NW-SE
Dimension (LxHxW) [m]	23x32x14	30x19x13
Net Air Volume [m³]	7391.6	4431.9
N floors	9	5
N openings	54	45
Window-to-wall ratio [-]	0.30	0.22
Opening area (avg) [m²]	2.88	2.97

In this work, the hourly weather data has been provided by the weather station of Politecnico di Torino. It is located at a height of 32 m from the ground in the same district (Crocetta) of the two selected buildings. For this reason, the coefficient δ and υ for the weather station and the two buildings are the same reported in Table II.

TABLE IV. WEATHER DATA FOR THE YEARS 2013-2014

Weather input data								
	T_{avg} [°C]		**I_{sol} [W/ m²]**		**WindDir [°] (freq %)**		**Vws [m/s]**	
	2013	*2014*	*2013*	*2014*	*2013*	*2014*	*2013*	*2014*
1	5.0	6.1	60.2	49.3	22.5 (41%)	22.5 (34%)	1.18	0.99
2	4.3	7.4	85.6	78.6	22.5 (29%)	22.5 (29%)	1.23	1.22
3	8.2	12.3	114.4	150.5	22.5 (22%)	22.5 (26%)	1.19	1.39
4	13.9	15.8	143.3	178.5	22.5 (17%)	22.5 (22%)	1.32	1.44
5	16.3	18.0	212.8	218.7	22.5 (16%)	22.5 (21%)	1.63	1.40
6	22.4	22.7	246.5	230.5	292.5 (18%)	337.5 (18%)	1.59	1.73
7	26.0	22.7	248.9	210.5	22.5 (19%)	22.5 (19%)	1.61	1.47
8	24.8	22.5	231.1	188.7	337.5 (17%)	292.5 (20%)	1.54	1.47
9	20.8	20.4	163.0	154.0	292.5 (16%)	292.5 (18%)	1.35	1.32
10	15.0	16.7	73.4	94.1	22.5 (21%)	22.5 (18%)	0.96	0.99
11	9.8	11.1	60.3	49.7	22.5 (23%)	22.5 (32%)	1.21	0.97
12	6.0	6.8	54.6	46.0	22.5 (46%)	22.5 (34%)	0.99	1.04

The monthly climatic input data used in the model to evaluate the natural cross-ventilation by infiltrations of buildings are reported in Table IV. As the heating season considered in this study refer to 2013-14 (15th Oct – 15th Apr), the monthly climatic data have been collected for both years. In the columns *WindDir* of Table IV, the terms in brackets indicate the frequency of the values of the wind direction angle on the total hourly measurements of each month.

A shown in Figure 5, the presented methodology (see paragraph C) has been applied for the calculation of the azimuth (Az) of the two buildings, according to their orientations and determining the windward façade in relation to the three prevailing wind direction (22.5°- 292.5°- 337.5°) from Table IV. Considering only the months of the heating season (Oct 13-Apr 14), in this case study there is a unique prevailing wind direction (22.5°) to be applied to calculate pressure coefficients.

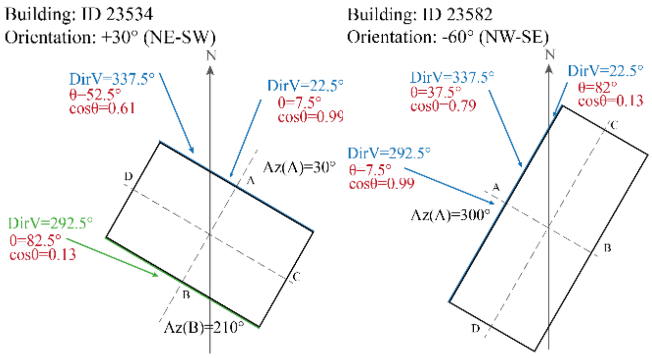

Fig. 6. Azimuth angle (Az) and wind incident angle (θ) for the three prevailing wind direction angles (DirV) and for the two building orientations NE-SW (on the left) and NW-SE (on the right).

IV. RESULTS AND DISCUSSION

Table V shows the results for the two-case studies of the average value of wind pressure coefficient Cp for the heating season 2013-14, considering separately each floor (F) [12]. The monthly wind direction (DirV) for all months of this heating season correspond to 22.5°N and the orientations of windward (WF) and leeward (LF) façades are indicated in the second column. Higher values can be observed as the floor increases and this is due to the rise of wind speed, especially on the windward (WF) façades.

TABLE V. AVERAGE MONTHLY PRESSURE COEFFICIENT CP

Building		**F1**	**F2**	**F3**	**F4**	**F5**	**F6**	**F7**	**F8**	**F9**
ID 23534	**W 30°**	0.040	0.027	0.014	0.025	0.042	0.104	0.191	0.284	0.409
	L 210°	-0.024	-0.027	-0.027	-0.028	-0.026	-0.028	-0.032	-0.045	-0.049
ID23582	**W 300°**	-0.051	-0.018	-0.051	-0.172	-0.247	-	-	-	-
	L 120°	-0.063	-0.079	-0.081	-0.079	-0.087	-	-	-	-

In Table VI are shown the results for the two-case study buildings of the average monthly achs for the heating season 2013-14, considering separately the daily (d) and night (n) values of ach. It is possible to observe high differences of +41% of air changes per hour between the months, then an annual average value of ach could not be adequately accurate.

TABLE VI. AVERAGE MONTHLY ACH IN THE HEATING SEASON 2013-14

Building		**Oct-13**	**Nov-13**	**Dec-13**	**Jan-14**	**Feb-14**	**Mar-14**	**Apr-14**
ID 23534	**d**	0.229	0.287	0.234	0.235	0.289	0.330	0.342
	n	0.120	0.118	0.126	0.120	0.148	0.169	0.175
ID23582	**d**	0.012	0.015	0.012	0.012	0.015	0.017	0.018
	n	0.010	0.013	0.010	0.010	0.013	0.015	0.015

Table VII shows the resulting average seasonal achs for the two buildings compering all scenarios. Especially for building ID23582, not well exposed to the wind, the ach is not sufficient to guarantee good air quality conditions inside the building; therefore, with scenario "m_d&n+o" the windows have been opened 3 times a day for 15 minutes (at 7 a.m. and at 2 and 9 p.m.) [3].

TABLE VII. AVERAGE SEASONAL ACH FOR DIFFERENT SCENARIOS

Building	*ach=0.5 h^{-1}*	*ach(m)*	*ach(m_d&n)*	*ach(m_d&n+o)*
ID 23534	0.5	0.276	0.225	0.466
ID23582	0.5	0.0145	0.0136	0.276

In Figure 7, the monthly energy needs (MWh) for space-heating for the 4 scenarios of natural ventilation were compared. It can be seen how important it is to vary the monthly natural ventilation ach of buildings. For the wind-exposed building ID 23534, with the proposed assessment, the relative error on energy consumption goes from 20.2% with "ach=0.5 h^{-1}" to 11% with "ach(m_d&n+o)", 0.9% with "ach(m)" and 0.6% with "ach(m_d&n)". With the other building ID 23582, the scenario "ach=0.5 h^{-1}" has an error of -7.3%; it works better because the effect of the wind is not sufficient for the air quality requirements; only by introducing three openings of the windows an error of -16.5 % is reached.

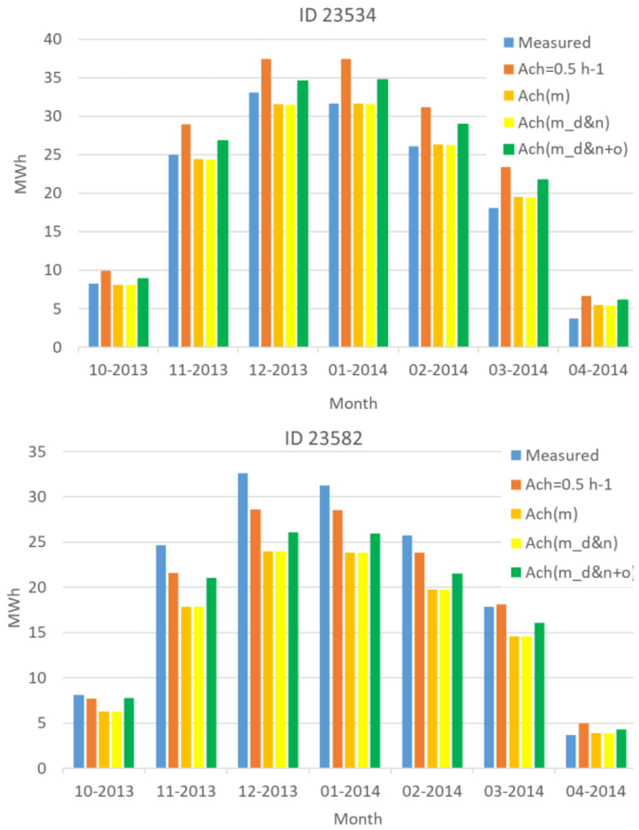

Fig. 7. Energy needs for space heating for the two case-studies considering four scenarios of natural ventilation by infiltrations and window openings.

V. Conclusions

This work introduces a methodology to evaluate the ventilation loads at building scale and to assess the monthly air change per hours, according to the climatic condition, the building orientation, shape and permeability, and the urban morphology of the surrounding context. The monthly variation of ach is here used as an improvement to the place-based model for assessing the energy demand of residential buildings for space heating both at building and urban scale. The methodology was applied to two buildings differently oriented, considering the prevailing monthly wind direction and relative velocity. In this work, only the wind-driven effect has been used to assess the air flow rate. Then, the orientation and the height of the building affect the monthly variation of air change per hour. Results show that the ach is not constant during the heating season and its monthly variation makes it possible to improve the place-based engineering model in predicting the energy performance of buildings.

As this model has already been applied at the block of building scale, in future works the methodology here presented will be adapt to a larger scale. In addition, the ventilation loads at building and block of building scale can be assessed at the monthly and hourly time scale, adapting the monthly and hourly place-based model for both the heating and cooling season.

Among the further developments of this introductory work, there are:

- consider a greater number of the wind rose sectors to have diversified and more precise input data of the incident wind direction
- consider in a more detailed and diversified way the characteristics of the façade openings and leakages, both in terms of size and typology
- consider internal partition and connection between the building floors (e.g., the stairwell), and consequently assessing the air flow rate considering the stack effect and the gradient of temperature inside and outside the building
- use GIS tools to evaluate the wind effects on buildings' facades at neighbourhood-district scale.

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