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Field studies on the effect of built forms on urban wind environments

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ABSTRACT

Airflow through urban environments is one of the most important factors affecting human health, outdoor and indoor thermal comfort, air quality and the energy performance of buildings. This paper presents a study on the effects of wind induced airflows through urban built form using statistical analysis. The data employed in the analysis are from the year-long simultaneous field measurements conducted at the University of Reading campus in the United Kingdom. In this study, the association between typical architectural forms and the wind environment are investigated; such forms include: a street canyon, a semi-closure, a courtyard form and a relatively open space in a low-rise building complex. Measured data captures wind speed and wind direction at six representative locations and statistical analysis identifies key factors describing the effects of built form on the resulting airflows. Factor analysis of the measured data identified meteorological and architectural layout factors as key factors. The derivation of these factors and their variation with the studied built forms are presented in detail.

1. Introduction

The interaction between an approaching wind with the building settlements determines urban wind patterns. Within an urban canopy (defined here as the space around the buildings below roof level), the formation of an urban wind environment is important for human health, outdoor and indoor thermal comfort, air quality and the energy performance of buildings [1–3]. For example, the cooling effect of urban wind, especially at night, helps to mitigate the adverse effects of an urban heat island on human thermal comfort both indoors and outdoors. Also, a favourable urban wind pattern indirectly contributes to the reduction of carbon dioxide emissions as passive, natural, indoor ventilation reduces the need for mechanical air conditioning [4,5]. Moreover, air pollution in the urban environment is most effectively dissipated by appropriate distribution of wind induced airflows [6–8].

It is a well-observed fact that a prevailing regional wind changes its pattern as it flows through a built environment [9]. In general, three regimes of urban wind are classified in literature [10]; depending on the urban building intensity, they are: (i) isolated roughness flow; (ii) wake interference flow and (iii) skimming flow, which are classified by the ratio (H/W) of building height (H) to the distance between building arrays (W). The wind velocities and flow patterns are not only dependent on weather conditions but also on the occurrences of different flow regimes, including the wind speed and geometrical variables related to the buildings in settlements and open spaces [11]. These variables related to the open space in urban settlement are dimensions of the open space, shape and placement, which are determined by the built forms [12]. Unlike a street canyon in a general urban form, buildings create different levels of resistance to the airflow at different locations due to their different shapes and sizes, and their relative layout with respect to each other. An understanding of the relationship between built forms and wind induced airflow is important, as it will benefit the understanding of the cooling and ventilating effects of urban wind. However, apart from the physical obstruction of the buildings to the airflow, the variation of urban surface temperatures also affects the urban wind.

Experimental studies have been carried out at the University of Reading campus, UK, from 2009 to 2010. A year-long, simultaneous, on-site, wind measurement data collection process at six locations

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Nomenclature

V_1	the wind speed of the first measured station, m/s
V_2	the wind speed of the second measured station, m/s
V_3	the wind speed of the third measured station, m/s
V_4	the wind speed of the fourth measured station, m/s
V_5	the wind speed of the fifth measured station, m/s
V_6	the wind speed of the sixth measured station, m/s
V_{w2}	the wind speed at the height of 2 m, m/s
$V_{w3.5}$	the wind speed at the height of 3.5 m, m/s
V_{w10}	the wind speed of the meteorological station at the height of 10 m, m/s
f_1	the meteorological factor
f_2	the architectural layout factor
E	east
W	west
S	south
N	north
n	the power index between the wind speed and the height
KMO	Kaiser-Meyer-Olkin (a test to assess the appropriateness of using factor analysis on data)
df	degree of freedom (test to assess the appropriateness of using factor analysis on data)
Sig	significance level (test to assess the appropriateness of using factor analysis on data)

within a cluster of building blocks provided 105,120 sets of data including wind speed and direction for statistical analysis. This paper attempts to discuss the effect of built form on urban canopy wind field using statistical analysis.

1.1. Brief literature review

Studies which look at the effect of the built form on wind fields, mainly focus on a combination of field measurement and the simulation method [13–17] along with some wind-tunnel and field experimental studies [18–20]. There have been few attempts at a statistical analysis of the relationship between urban winds and different built forms. Jones *et al.* [19] used wind-tunnel scale modelling and numerical computational fluid dynamics (CFD) to simulate and assess the pedestrian wind environment and found that the two methods yielded broadly similar results in predicting wind-flow patterns through the complex. In addition, wind factors of up to three times the free-site wind speed were predicted by both methods. Kubota *et al.* [20] investigated the relationship between the average wind speed at pedestrian-level and building density of actual residential neighbourhoods based on several wind-tunnel experiments. The study produced data that emphasised the strong relationship between the coverage ratio and the mean wind velocity ratio; when this ratio increased, the wind speed on-site decreased. However, there were some disagreements in the detailed location and extent of the severe areas, which indicates that further investigation and validation are required before CFD methods can be comfortably used in practice. Omar and Asfour [16] carried out a parametric three-dimensional CFD modelling study to investigate the effect of building grouping patterns on the formation of the wind environment in outdoor spaces and the potential ventilation passive cooling effect on these buildings. The study found that by grouping patterns of buildings as well as their orientation with respect to wind, a dramatic effect on the formation of airflow behaviour and pressure fields was achieved. Zhang *et al.* [21] carried out a CFD simulation and wind-tunnel study to examine wind patterns around different building arrangements. The study obtained the maximum wind speed and vortex on the windward surface through numerical simulation of seven buildings in parallel arrays with rectangular cross-section at Xi'an Jiaotong University and found that the wind environment around the buildings strongly depended on building layout and wind direction. Ma [22] adopted a numerical simulation method based on the Reynolds time-averaged equation and renormalization group (RNG) k-ε turbulence model to analyse the wind environment of a building complex composed of six high-rise buildings with quadrate sections. By changing the horizontal distance between each column, for buildings which were initially in two rows and three columns, he obtained eight different grouping patterns of the buildings. The wind speed ratio and velocity vector field at pedestrian height (2 m) of surrounding buildings were compared. The results showed that the wind environment was more beneficial when the six buildings were in an 'S' pattern or in two parallel rows (paratactic type); whilst a 'Y' shaped form or semi-closure leads to a serious roadway effect. Zhang *et al.* [17] proposed a new scheme for realizing real-time boundary conditions to study the airflow and pollutant dispersion characteristics in an urban street canyon. They found that the flow had an obvious intermittent feature in the street canyon and that flapping of the shear layer forms near the roof layer under real-time wind conditions, resulting in the expansion or compression of the air mass in the canyon. Nelson *et al.* [18] used three-dimensional sonic anemometers under unstable atmospheric conditions to produce velocity spectra, cospectra and weighted joint probability density functions. They also found a low-frequency peak that appears to be associated with vortex shedding of the buildings and a mid-frequency peak generally associated with canyon geometry. The low-frequency peak was found to produce a counter-gradient contribution to the along-wind vertical velocity covariance. In addition, the standard spectral tests for local isotropy indicated that isotropic conditions occur at different frequencies depending on spatial location, demonstrating the need to be thorough when testing for local isotropy within the urban canopy.

The objective of this study is to identify key factors for the effect of the built form on wind environment in low-rise building blocks. The built form affects airflow distribution within a city in terms of building orientation, distances between buildings and group arrangement. Also, the design of a building complex affects the natural ventilation and airflow distribution (namely "building wind") of building blocks in terms of the space layout and architectural form.

To achieve these objectives, a statistical analysis method has been applied to identify key factors of the effects of the built form on the wind environment. In this study, factors describing the meteorological and architectural layout are identified for three built forms: a street canyon, a semi-closure, a courtyard form and an open space (Fig.1). Recently, Turkbeyler and Yao [23] experimentally studied the urban microclimate of a building complex at the University of Reading, UK. The building complex studied, consisted of six buildings that represent the typical built

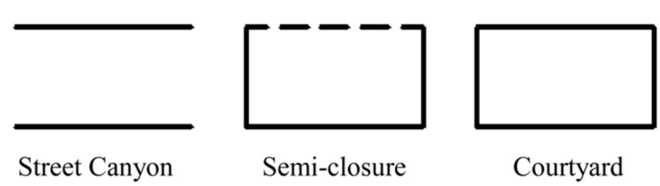

Fig. 1. Three architectural built forms.

forms: street canyons, semi-closures and courtyard-like forms. The present statistical analysis is based on the measured data from this experimental study.

1.2. Research methods

Details of the experimental data in the aforementioned study [23]are presented below.

1.3. Location of the field study

The experimental field study area was located at a building complex within the University of Reading campus in the United Kingdom (Fig.2). Building blocks A, B, C, D, E, and F are 12 m, 7 m, 7 m, 7 m, 3.5 m, and 7 m high, respectively. The following building blocks create different built forms:blocks A, B, and E constitute a street canyon, blocks A, C, E and F constitute a semi-closure and blocks B, C and D constitute a form. The space to the north side of block A is a relatively open courtyard form. The street canyon axis is oriented at an angle of 17.5° clockwise from an east-west direction.

1.4. Parameters of measurement

Wind speed and direction were measured at six locations on the building complex; these are donated by the red numbers 1–6 (Fig.2). The five measurement stations (1–5) were assigned to monitor the three kinds of architectural layout: stations 1 and 2 were located in the street canyon; station 3 was located in the semi-closure and stations 4 and 5 were in the courtyard form. In the courtyard form, station 4 was positioned closer to the building, compared to station 5.

1.5. Measuring instruments and data acquisition

At each measurement station, wind speed and wind direction were measured continuously over a period of one year, from April 2009 to March 2010 without any interruption. Each point featured a wireless weather-station which continually recorded wind data at 5-min intervals at a height of 3.5 m above ground level. The wind speed and direction measurements achieved a precision of 5% of any measured value (or 0.1 m/s, whichever was greater) and 1°, respectively. Wind speed was measured using a rotational cup and wind direction using a low friction wind vane. Fig. 3 shows one of the wireless weather-stations at the experimental site. In addition, the meteorological data at an isolated location on the university campus was also monitored independently by the university's principle observatory. The set of measurements at the university observatory, which is 600 m away from the studied building complex, was considered as the local reference value for the experimental site.

1.6. Statistical analysis

In this study, the variation of observed wind measurement are statistically analysed to determine both the meteorological factor and the architectural layout factor of the built forms affecting the wind pattern within the building complex. Firstly, wind-rose diagrams for these experimental measurements were constructed to comparatively analyse the wind-speed and direction data at all six measurement points. Secondly, based on these wind-rose diagrams, the SPSS correlation analysis method [24,25] was used to analyse the velocity at the six measurement stations and the university meteorological observatory station. Correlation analysis is a statistical method to identify relationships between variables so that they reflect the variation of one variable when another variable is controlled. A close relationship between variables may thus be obtained, and then an overall relationship can be deduced based on the sample. Finally, based on the results of the correlation analysis, the statistical method of factor analysis has been used to identify the meteorological factors and the architectural layout factors of

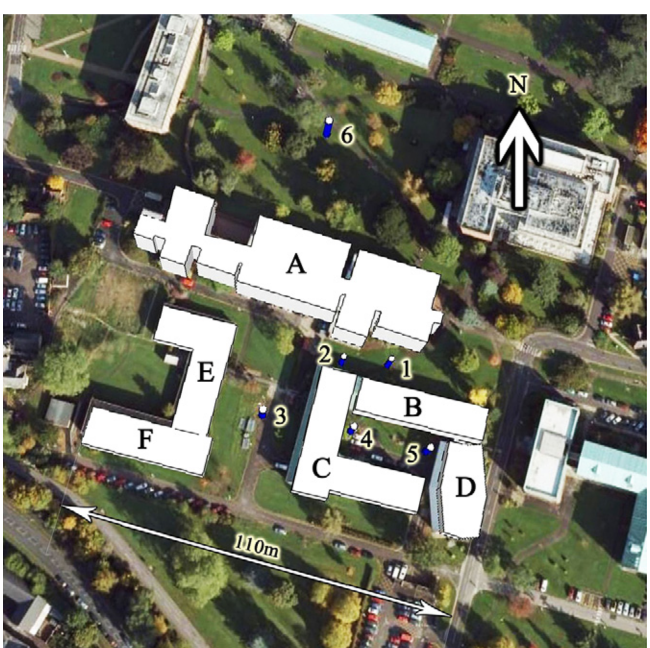

Fig. 2. Layout of the measurement site.

Fig. 3. Wireless weather-station at the experimental site (location1).

the built forms. Factor analysis is generally used to describe variability among observed variables in terms of a potentially lower number of unobserved variables called "factors". It is used in this paper to identify the *factors* that influence the wind speed at the six measurement stations.

2. Results and discussion

2.1. Preliminary observations

Initially, the experimental data (wind speed and direction from all six measurement stations) and the university meteorological observatory data have been displayed in wind-rose diagrams. The wind-rose diagram is the common method for displaying the distribution of the wind speed and its direction at a specific location over a period of time. Wind roses typically use 16 cardinal directions, (eg. north [N], northeast [NE] and north northeast [NNE] etc.) to show the frequency of winds blowing from each direction over a specified period. The length of each "spoke" around the circle is related to the frequency that the wind blows from a particular direction per unit time. Each concentric circle represents a different frequency, emanating from zero at the centre to increasing frequencies at the outer circles. The direction of the rose with the longest spoke shows the wind direction with the greatest frequency. A wind-rose plot may contain additional information whereby each spoke is broken down into colour-coded bands that show wind speed ranges.

Fig. 4 shows the wind-rose diagrams of wind speed and direction at the six measurement stations within the experimental site as well as that from the university observatory station. From this, we can see that the dominant wind direction is different for each built form. The ratio H/W of station 1, station 2, station 3, station 4, station 5 and station 6 are 0.8, 0.6, 0.2, 0.18, 0.18, and 0.48 respectively. The local dominant wind direction from the meteorological observatory station it is southwest (SW) with a wind speed greater than 2 m/s but the dominant wind direction at station 1, station 2, station 3, station 4, station 5 and station 6 become west (W), west (W), south (S), northeast (NE), south-south-east (SSE) and northeast (NE) respectively. However, it is observed from these diagrams that the wind speeds at the measurement stations are relatively slower than that measured from the observatory station. It is obvious that the buildings influence the immediate wind pattern, causing a change in speed and direction, when compared to the local wind pattern observed by the university's meteorological observatory which located in relatively open space.

2.2. Wind speed and direction analysis

It can be seen from Fig. 4 that the frequency of wind speeds greater than 2 m/s at the observatory station accounts for 56.7% of total measurements. On comparison, this is far greater than values at the six other measurement stations in the built up areas. For the street canyon built form, stations 1 and 2 (with slightly higher H/W ratio) were sheltered by buildings against local winds from the SW direction. The frequency of the wind speeds greater than 2 m/s is about 21.6% and 10.9% respectively. Building A and B caused changes in the wind direction and attenuation of speed in the street canyon. Thus, at station 1and 2, the wind direction become westerly (W), and the wind speed slowed; the frequencies of wind speed less than 1 m/s at these two stations are 51.9% & 67.7% respectively. For the semi-closure built form, represented by station 3, the frequency of wind speeds greater than 2 m/s is 11.7%. The dominant wind direction is in accordance with the local leading wind direction. For the courtyard built form, represented by stations 4 and 5, the natural wind inside the square formed a vortex due to the relatively isolated layout form. Station 4 and Station 5 have different dominant directions because there is an opening nearby. Within the courtyard, the wind speeds are mostly less than 1 m/s with frequencies of 93.5% and 80.3% respectively. The courtyard's form has a significant impact on the reduction of wind speed.

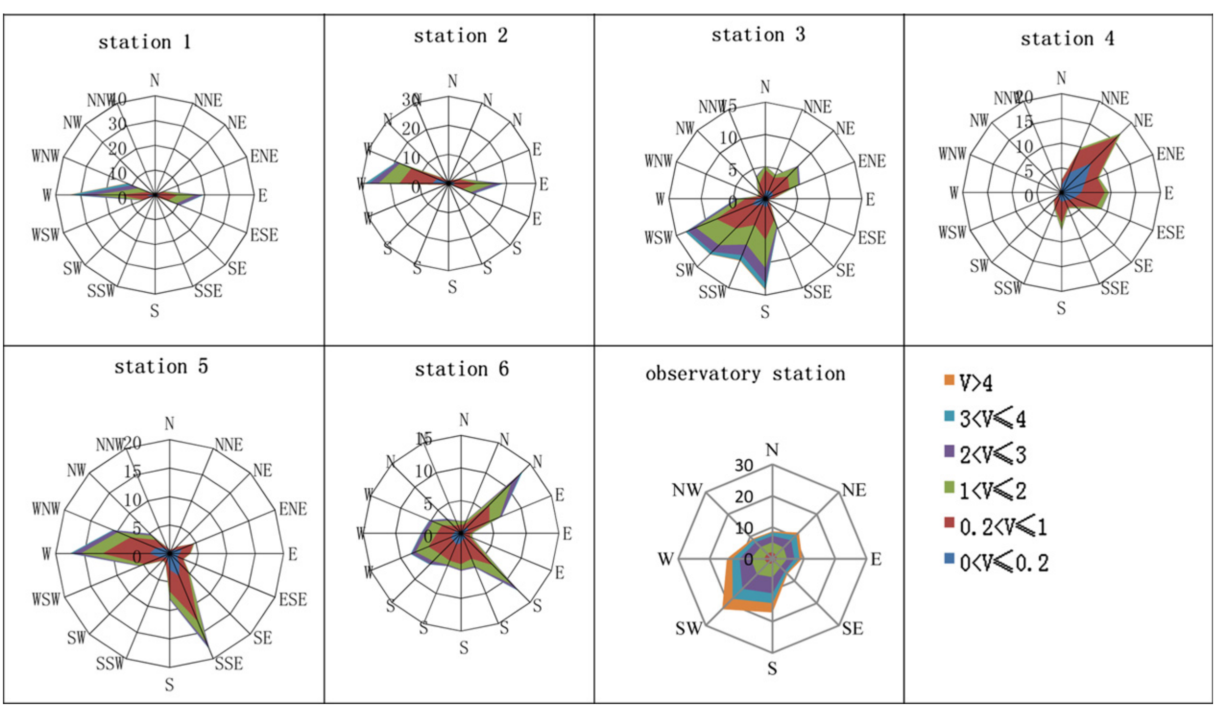

Fig. 4. Wind rose diagrams showing the distribution of wind speed and direction at the measurement sites between 1st April, 2009 and 31st March, 2010.

Table 1
The dominant wind and a frequency of different architectural layouts in different leading wind directions.

Observation	Station 1	Station 2	Station 3	Station 4	Station 5	Station 6
N	E(44.4%)	W(39.1%)	N(37.6%)	O(39.8%)	W(33.6%)	NE(57.5%)
S	W(49.2%)	W(27.9%)	S(70.9%)	E(30.3%)	S(39.9%)	SE(46.5%)
E	E(77.9%)	E(79.3%)	NE(36.8%)	S(55.4%)	E(32.9%)	NE(40.8%)
W	W(88.5%)	W(85.3%)	SW(40.6%)	O(38.8%)	W(69.4%)	W(34.8%)
NE	E(78.1%)	E(72.1%)	NE(53.9%)	O(28.2%)	W(30.5%)	NE(71.1%)
SE	E(65.4%)	E(72.2%)	S(64.3%)	S(32.8%)	SE(34.7%)	SE(57.3%)
SW	W(85.4%)	W(67.4%)	SW(53.1%)	NE(32.4%)	W(36.8)	SW(25.7%)
NW	W(79.7%)	W(82.2%)	N(30.1%)	NE(51.0%)	W(40.1%)	O(26.5%)

Note: O = there is no predominant wind direction.

In summary, the different architectural forms on the complex produced significant differences between the dominant wind direction at each measurement point and the university's meteorological observatory station. Furthermore, the wind speed frequency range is dissimilar (Table 1). For example, when the wind direction at the Meteorological Observatory is South (S), the leading wind direction in the Street Canyon (station 1 and station 2) is West (W) and the wind frequencies at stations 1 and 2 are 49.2% and 27.9%, respectively. At the same time, the leading wind direction in the semi-closure layout (station 3) is South (S) and the wind frequency at station 3 is 70.9%. However, in the courtyard situation, the leading wind directions at station 4 and station 5 are different, with frequencies of 30.3% west wind and 39.9% of south wind, respectively. It is worth noting that, when the wind speed is zero at the stations (i.e. the steady still condition) "O" is used to represent its frequency. Therefore, it can be concluded that the architectural layout, or the built form, the height of the building and the urban meteorological conditions have a great influence on the wind environment of urban building blocks.

2.3. Factor analysis of wind speed

Based on the year-long measurement data from the six stations, the relationship between urban winds and built forms, as well as the micro-wind environment, has been investigated using the statistical methods of correlation analysis and factor analysis.

2.4. Correlation analysis of wind speed at the measurement stations and the meteorological station

The SPSS correlation analysis method has been used to analyse wind speed at the same moment for the six measurement stations and the meteorological station. The wind speed at the height of 3.5 m could be obtained by equation (1) [26], and the power index 'n' can be obtained by equation (2), where the wind speeds at the height of 2 m and 10 m were measured at the meteorological station. According to reference [24], correlation between the factors exists when the correlation coefficient is greater than 0.5. Table 2 lists the correlation coefficient between the wind speeds at the six experimental stations and the observatory station. All the correlation coefficients exceed 0.5. From Table 2 we can see that station 2 is in a whirlpool area, and the correlation coefficient of wind speeds between this station and the observatory station is 0.660. Station 4 was in the courtyard form, 1 m away from the surrounding exterior wall, and the correlation coefficient of wind speeds between this station and the observatory station is 0.707. Station 3 was in a semi-closure, and the correlation coefficient of wind speeds between this station and the observatory station is 0.842, which is a high correlation. From Fig. 2 it can be seen that point 6 was in a relatively open area surrounded by four buildings, the distance between point 6 and the nearest wall is about 40–60 m. The influence of the courtyard- form is less than that of points 4 and 5 because it is located in a less dense area than stations 4 and 5. The correlation coefficients between the wind speeds in all the other stations to the observatory station are greater than 0.74. From this analysis, we can see that there exists a correlation of the wind speeds between each local station and the observatory station; station 3 in the semi-closure has the most significant correlation. A correlation also exists between local stations, though their coefficients are less significant.

Table 2
Correlation coefficient matrix.

Pearson correlation	V_1	V_2	V_3	V_4	V_5	V_6	$V_{w3.5}$
V_1	1	0.754	0.692	0.629	0.749	0.750	0.768
V_2	0.754	1	0.576	0.678	0.694	0.713	0.660
V_3	0.692	0.576	1	0.699	0.756	0.702	0.842
V_4	0.629	0.678	0.699	1	0.620	0.618	0.707
V_5	0.749	0.694	0.756	0.620	1	0.730	0.743
V_6	0.750	0.713	0.702	0.618	0.730	1	0.773
$V_{w3.5}$	0.768	0.660	0.842	0.707	0.743	0.773	1

$$V_{w3}\cdot 5 = V_{w10}\left(3\cdot\frac{5}{10}\right)^{n} \tag{1}$$

$$\mathrm{n} = \ln(V_{\downarrow}w2/V_{\downarrow}w10)/\ln(2/10) \tag{2}$$

2.5. Factor analysis of the wind speed at the six measurement stations

According to the principle of the factor analysis method, six highly-correlated speeds of the measurement stations are selected as the factors for reduced-order analysis. All speeds are converted to several unrelated factors with constant total variance. The first main component has the maximum variance, whereas the data variation interpreted by other extracted components gradually decreases.

First, the necessary conditions of factor analysis must be satisfied, which are theKaiser-Meyer-Olkin (KMO) value test and the Bartlett's Test. The KMO measure of sampling adequacy tests whether the partial correlations among variables are small. If the threshold of KMO is greater than 0.5, then factor analysis is applicable; if the threshold of KMO is greater than 0.7, then the factor analysis effect is improved. Bartlett's test of sphericity examines whether the correlation matrix is an identity matrix, which can indicate whether the factor model is appropriate or not. Bartlett's test of sphericity includes three parameters: Approx. Chi-Square, degree of freedom and the significant level. When the degree of freedom is 15, the significant level should be greater than 25 and the significance should be less than 0.05 [24]. The KMO and Bartlett's Tests should both meet the above requirements for

Table 3
KMO and Bartlett's Test.

Kaiser-Meyer-Olkin measure of sampling adequacy		0.879
Bartlett's Test of sphericity	Approx. Chi-Square	456387.153
	df	15.000
	Sig.	<0.001

a satisfactory factor analysis to proceed. Table 3 lists the results of the tests, from Table 3 we can see that the KMO is 0.879, which is much greater than 0.7 and the Bartlett's test of sphericity is significant with the associated probability less than 0.001, which is much less than the 0.05 threshold. This means that the measured data are suitable for the application of factor analysis [24].

Secondly, common degrees are analysed for $V_1 \sim V_6$. Common degrees refers to the common factor variance satisfaction, it reflects the part interpreted by common factors, the larger the common degrees, the better the factor analysis [25]. Table 4 shows common degrees for $V_1 \sim V_6$, the initial value is the total variance interpreted quantity before extracting factors; the extraction value is the proportion of the amount of variance explained by the two common factors. If the extraction value is greater than the threshold, which is 0.5, then the common factors are very well extracted. In this study, the extract value is 0.7, which is greater than the threshold value (see Table 4). It shows a good resolution of factor analysis.

Thirdly, the accumulative total variance contribution is used to determine the number of factors. The number is sufficient until it is greater than 80%, namely 20% loss of information. There are two principal components (f_1 and f_2) for the measured wind speeds at the 6 stations, which can explain 81.878% of the variance (see Table 5).

Finally, the principal component analysis (PCA) method has been applied and followed by calculating variance to identify key factors, which are expressed by Equations (3)–(8).

By applying factor analysis, two common factors for the wind speed at the six stations (Equations (3)–(8) have been identified with the order of f_1 and f_2 being fixed. According to correlation analysis in Table 2, we can identify that station 3 has a high correlation coefficient of 0.842 between its wind speed and that at the observatory station (Equations (3)–(8), meanwhile, from Equation (5) we can see that the coefficient (0.851) of f_2 is greater than that of f_1 (0.394). Therefore, f_2 is identified as the meteorological factor and f_1 as the architectural layout factor.

$$V_1 = 0.816f_1 + 0.413f_2 \tag{3}$$
$$V_2 = 0.854f_1 + 0.319f_2 \tag{4}$$
$$V_3 = 0.394f_1 + 0.851f_2 \tag{5}$$
$$V_4 = 0.379f_1 + 0.809f_2 \tag{6}$$
$$V_5 = 0.673f_1 + 0.571f_2 \tag{7}$$
$$V_6 = 0.765f_1 + 0.453f_2 \tag{8}$$

From equations (3)–(8), two common factor states for the coefficients of $V_1 \sim V_6$ are different due to the various architectural layouts. For the street canyon architectural layout (stations 1 and 2), the coefficient of the architectural layout factor f_1 is obviously higher than the coefficient of the meteorological factor f_2; in other words, f_1 is the factor with a greater influence on wind speed. For the semi-closure pattern architectural layout (station 3), the coefficient of f_1 is less than that of f_2, that is, f_2 has a greater influence on wind speed. For the courtyard architectural layout, station 4 is greatly influenced by the meteorological factor f_2, however factors f_1 and f_2 have an almost equal influence on wind speed for station 5. It is worthwhile to mention that station 4 was close to the narrow pathway leading to the courtyard, the 'gap' may cause meteorological factor f_2 to become dominant at this point. Station 6 can be regarded as located in a less dense, courtyard form. In this station, the architectural layout factor f_1, is greater than the metrological factor f_2. Further studies will be carried out using Computational Fluid Dynamics regarding the influences of the built form factor and the meteorological factor in the courtyard form.

Table 6 summarises the architectural form factor f_1 and meteorological factor f_2, on the three studied forms.

Table 4
Commonalities.

	Initial	Extraction
V_1	1.000	0.837
V_2	1.000	0.831
V_3	1.000	0.879
V_4	1.000	0.797
V_5	1.000	0.778
V_6	1.000	0.791

Table 5
Total variance explained.

Component	Initial Eigen values			Extraction sums of squared loadings		
	Total	% of variance	Cumulative %	Total	% of variance	Cumulative %
1	4.456	74.272	74.272	4.456	74.272	74.272
2	0.456	7.606	81.878	0.456	7.606	81.878
3	0.427	7.113	88.991			
4	0.266	4.439	93.430			
5	0.229	3.820	97.251			
6	0.165	2.749	100.00			

Table 6
The impact of meteorological factor and architectural factor on the grade of wind speed.

Layout (direction of the opening)	The architectural layout factor (f_1)	The meteorological factor (f_2)
Street-canyon (W-E)	Stronger	Weaker
Semi-closure (W)	Weaker	Stronger
Courtyard	Slightly stronger	Slightly weaker

3. Summary and conclusion

The analysis of wind direction and wind speed derived from wind-rose diagrams for six measurement stations at a low-rise building complex in Reading, UK shows that changes in dominant wind direction would produce differences among their wind directions and wind speeds within the architectural complex.

This research has analysed changes of speed and direction of the dominant wind due to different architectural built forms. The dominant wind direction at the street canyon built form is significantly different to that at the observatory station which describes the local meteorological conditions. The leading wind direction at the courtyard built form varies frequently in this case, because of turbulence created by a 'gap' into the courtyard which allows air flow into it.

Correlation analysis shows that if wind measurement points are located in a low-rise building site, there is a correlation between the wind speeds at these measurement stations; in particular, there is a high correlation of the wind speed between station 3 in this instance, and the university's observatory station. Also, the common degree of wind speed at the measurement points are greater than 0.77. As a result, architectural layout factor f_1 and meteorological factor f_2 are identified as the main influential factors on wind speed for urban building complexes according to this statistical analysis. The coefficients of the common factors are not identical, as the architectural layouts are different. The degree of wind speed affected by the meteorological factor and the architectural layout factor of the different built forms mentioned above are different. Meanwhile, the degree of influence of both f_1 and f_2 is variable depending on the location of the measurement and the openness of the courtyard. For the street canyon architectural layout, the wind speed is influenced mainly by the architectural layout factor f_1 when its opening is inconsistent with the direction of the meteorological wind direction. For the semi-closure architectural layout, the wind speed is influenced mainly by meteorological factor f_2. The findings from this experimental study are limited to the low-rise and low dense building complex.

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References

[1] Yang L, Li Y. Thermal conditions and ventilation in an ideal city model of Hong Kong. Energy and Buildings 2011;43(5):1139–48.
[2] Memon RA, Leung DYC. Impacts of environmental factors on urban heating. Journal of Environmental Sciences-China 2010;22(12):1903–9.
[3] Priyadarsini R, Hien WN, David CKW. Microclimatic modeling of the urban thermal environment of Singapore to mitigate urban heat island. Solar Energy 2008;8:727–45.
[4] Kolokotroni M, Giannitsaris I, Watkins R. The effect of the London urban heat island on building summer cooling demand and night ventilation strategies. Solar Energy 2006;80(4):383–92.
[5] Fung WY, Lam KS, Hung WT, Pang SW, Lee YL. Impact of urban temperature on energy consumption of Hong Kong. Energy 2006;31:2623–37.
[6] Vaughan S, Paul G, David M, Craig W. The relationships between indoor and outdoor respirable particulate matter: meteorology, chemistry and personal exposure. Indoor and Built Environment 2002;11(5):266–74.
[7] Branis M, Hovorka J, Rezacova P, Domasova M, Lazaridis M. Effect of indoor and outdoor sources on particulate matter concentration in a naturally ventilated flat (URBAN-AEROSOL Project Prague). Indoor and Built Environment 2005;14(3–4):307–12.
[8] Kato Shinsuke, Huang Hong. Ventilation efficiency of void space surrounded by buildings with wind blowing over buit-up urban area. Journal of Wind Engineering and Industrial Aerodynamics 2009;97(7–8):358–67.
[9] Patz JA, Campbell-Lendrum D, Holloway T, Foley JA. Impact of regional climate change on human health. Nature 2005;438:310–7.
[10] Oke TR. Boundary layer climates. Routledge; 1987.
[11] Ok V, özsoy A, Atll V, özgünler M, Serteser N, et al. An analysis of the effect of design parameters on wind speed and flow type in an urban open space. Istanbul: TUBITAK (Turkish Scientific and Technical Research Council) INTAG-214; 1996.
[12] Serteser N, Ok V. The effects of building parameters on wind velocity and air-flow type in the urban settlements: The Seventh International Conference on urban climate 29 June-3 July 2009, Yokohama, Japan.
[13] Li X, Zhou J, Shao J, Zhang Q. CFD-Based simulation analysis of indoor and outdoor ventilation environment. In: Proceedings of International Conference on computational Intelligence and Software Engineering (CISE 2010); 2010. p. 1–3.
[14] Yoshie R, Mochida A, Tominaga Y, Kataoka H, Harimoto K, Nozu T, et al. Cooperative project for CFD prediction of pedestrian wind environment in the Architectural Institute of Japan. Journal of Wind Engineering and Industrial Aerodynamics 2007;95:1551–78.
[15] Yoshihide T, Akashi M, Ryuichiro Y, Hiroto K, Tsuyoshi N, Masaru Y, et al. AIJ guidelines for practical applications of CFD to pedestrian wind environment around buildings. Journal of Wind Engineering and Industrial Aerodynamics 2008;96:1749–61.
[16] Omar S, Asfour. Prediction of wind environment in different grouping patterns of housing blocks. Energy and Buildings 2010;42:2061–9.
[17] Zhang YW, Gu ZL, Cheng Y, Lee SC. Effects of real-time boundary wind conditions on the airflow and pollutant dispersion in an urban street canyon-large eddy simulations. Atmospheric Environment 2011;45(20):3352–9.
[18] Nelson MA, Pardyjak ER, Brown MJ, Klewicki JC. Properties of the wind field within the Oklahoma City Park Avenue street canyon. Part II: spectra, cospectra, and quadrant analyses. Journal of Applied Meteorology and Climatology 2007;46(12):2055–73.
[19] Jones PJ, Alexander D, Burnett J. Pedestrian wind environment around high-rise residential buildings in Hong Kong. Indoor and Built Environment 2004;13(4):259–69.
[20] Kubota T, Miura M, Tominaga Y, Mochida A. Wind tunnel tests on the relationship between building density and pedestrian-level wind velocity: development of guidelines for realizing acceptable wind environment in residential neighbourhoods. Building Environment 2008;43:1699–708.
[21] Zhang A, Gu C, Zhang L. Numerical simulation of the wind field around building arrangements. Journal of Wind Engineering and Industrial Aerodynamics 2005;93:891–904.
[22] Ma J, Chen S. Numerical study of plan arrangement effect on wind environment around tall buildings. Journal of Zhejiang University (Engineering Science) 2007;41:1477–81 [in Chinese].
[23] Turkbeyler E, Yao R. Experimental study of urban microclimate for a building complex. In: Proceedings of the International Conference in Sustainable development in building and environment. China: Chongqing University; 2009. p. 38.
[24] Zhang WT. Statistical analysis SPSS Advanced Tutorial. Beijing: Higher Education Press; 2004. p. 213–227 (in Chinese).
[25] Xia Y. SPSS statistical analysis with example explanation right. Beijing Ministry of electronic industry press; 2010. p. 230–254 (in Chinese).
[26] Daven P. The relationship of wind structure to wind loading. In: Proceeding of the symposium on wind effect on building and structures. London; 1965. p. 54–102.