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**Article**

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# Campus wind environment evaluation in north China—A case study of NCUT

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## Abstract

Wind environment research in the populated urban area is an important topic on wind potential evaluation as well as wind comfort analysis. This study took measurement of 57 crossroad spots in the campus in North China University of Technology in Beijing. The data of wind speed and direction were measured at fixed time and fixed place. The spots of static wind zone, wake flow zone and risky zone were examined. The overall measured data in wind scale map was analyzed to find out the changes of wind speed and direction in different seasons and in different locations of the school. Research and analysis show that the overall wind environment of the campus at pedestrian level is in fair comfort: the average wind speed is between 0.04–4.8 m/s, though the overall frequency of campus wind comfort location measurement is not high. In addition, CFD simulations were undertaken in order to help identifying the wind risky points as well as wind potential at a high altitude. Three high-rise buildings were found with exploitable wind energy over roof. Averaged wind velocity on floor plan at 6m and 10m above roof were mostly bigger than 3m/s, which is favorable condition for wind energy exploitation. However, further detailed evaluation is necessary for the wind turbine installation position as there is much varieties on the evaluation level, building roof area and velocity distribution of each building.

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**Keywords:** Wind environment; Campus environment; CFD simulation; Wind energy potential

## 1. Introduction

University campus is an important place for college students to study and live in. The quality of the wind environment not only affects the normal development of teaching-practice activities, but also the learning and living environment as well as physical and mental health of college students and teachers. Du et al. [1] have conducted a close study of Hong Kong Poly University campus wind environment with CFD simulation. Regarding the comfort

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analysis of the wind environment, the “China Ecological Housing Technology Assessment Manual” stipulates that when the wind speed is less than 1 m/s (in the wind shadow area), the pedestrians basically do not feel the comfortable wind. Therefore, the basic outdoor wind speed generally needs to be more than 1 m/s, especially for hot and humid climate cities. Based on the research of green campus in his thesis, Xu [2] summarized the numerical evaluation criteria of wind speed in wind environment at pedestrian height in summer. In the cold weather in winter, the wind speed based on winter wind protection should be kept relatively low in the urban block area to prevent heat loss to meet the demand of thermal comfort. It is recommended that the wind speed in pedestrian level around the buildings (1.5 m high from the ground) be less than 5 m/s. At the same time, in order to facilitate the spread of air pollutants on the campus, the wind speed should be maintained above 1.0 m/s to ensure air quality. Regarding health, Lu [3] shows that for environmental sanitation, when the wind speed is lower than 0.4 m/s, it is not conducive to the discharge of pollutants in the air.

As early as the 1970s, Davenport [4] proposed an outdoor wind comfort criterion that defines the comfort sensation caused by different wind speed ranges for different types of activities. Based on the type of activity mentioned here, the Dutch Wind Disaster Standard [5] defines the wind comfort and safety at the pedestrian scale with a maximum wind speed of 5 m/s as the critical wind speed. Murakami et al. [6] found that wind speeds of 5–10 m/s have a certain impact on people based on the investigation of more than 2000 people. The wind speed of 10–15 m/s has a serious impact, while more than 15 m/s may cause very much serious impact. China’s “Green Building Evaluation Standards” MHURD [7] Article 8.2.8 stipulates that for the winter condition, the wind speed at a height of 1.5 m is suggested to be less than 5 m/s for pedestrian area around the building, and less than 2 m/s for outdoor activity areas and children playgrounds. Japanese scholar Murayama [8] has conducted abundant experimental research and found that the human body feels relatively comfortable at a height of 1.5 m in wind of 1–4 m/s. If it is below 1 m/s, it may cause discomfort due to weak wind (especially in summer). In summary, we can use 1–5 m/s as a better wind comfort zone, 5 m/s as the basic wind speed limit affecting people’s normal activities, and 15 m/s is the threshold of wind environment hazard.

In order to discover the problems of existing university campus wind environment, and to propose a better optimized wind environment plan for future campus planning, we take the North China University of Technology (NCUT) as the research object, and measure the wind speed level at different locations on the campus. The experimental data can help observe the wind distribution in the campus, tell the areas with poor wind environment from the ones with relatively good wind environment, and analyzes the causes of these phenomena. Apart from addressing to wind comfort environment, quantitative wind environment evaluation can also help discovering wind energy potential in the campus.

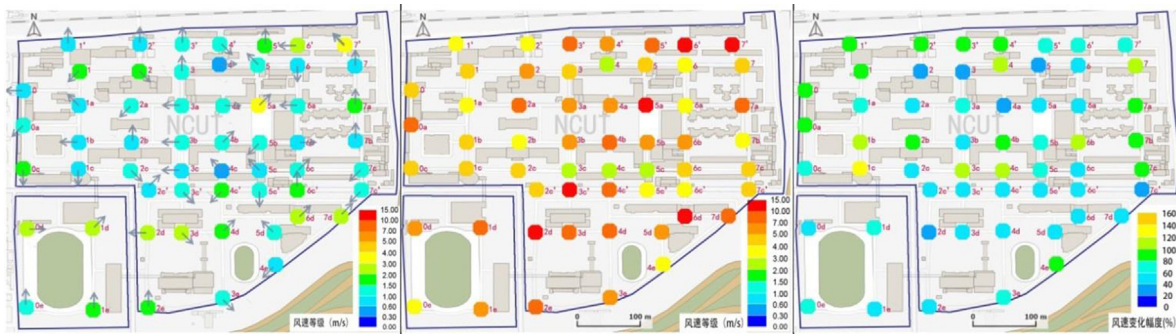
## 2. Methodology

The subject method includes measurement experiments and numerical simulation experiments. Field measurement experiments are conducted to obtain specific wind environment data, but are limited to the number and distribution of points. Numerical simulation experiments are used to assist in the analysis of wind environment data in more regions and at different evaluation heights. Though some errors exist between results of the simulation and the actual measurements, caused by inaccuracy in initial conditions setting and physical model representation, this study aims to discuss a method to evaluate wind environment in a dense campus by combining on-site measurement and numerical simulation.

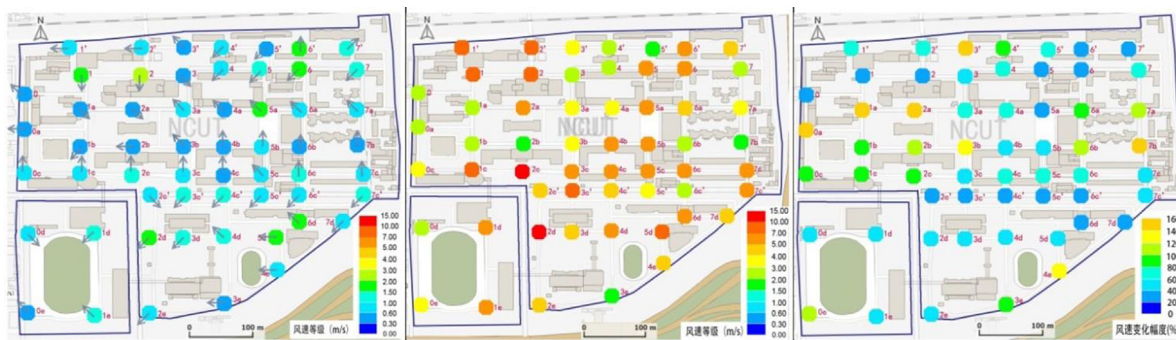
The measurement experiments were conducted through the school’s Open laboratory project, involving 20–30 students. The experiment selects the main road intersections in the campus of NCUT to measure the wind speed and direction of the pedestrian height (2 m). The campus is around 500 m × 500 m and has an L-form public road separating it into two parts. After two years, two seasons of spring (from March to June) and autumn (from September to November), a total of 20 days of samples are collected. Each measurement is approximately 1 week apart and the measurement time is essentially 16:30–17:30. The experimental measurements are the average wind speed, maximum wind speed and high frequency wind direction of each measure point. The wind gauge with wind vane can directly read the instantaneous wind speed with an accuracy of 0.1 m/s. The measurer observes the instantaneous wind speed digital change, and records the average value of the data appearing in around every five seconds. For each measurement point a total of 20 sets of average values, and the approximate range of the wind direction were recorded. Each measurement point takes about 2 min. There are 57 measuring points on the campus plane, and the measurement is performed in eight groups at the same time. The measurement interval between every two points is not more than 30 min.

### 3. Measurement results and analysis

According to the integration of the measurement data of the four semesters in the past two years, we can map the average wind speed and high-frequency wind direction distribution in the spring and autumn of the NCUT campus, the maximum wind speed distribution map and the wind speed variation distribution map (Figs. 1, 2).



**Fig. 1.** Spring campus session: measurement of the average wind speed distribution (left), maximum wind speed distribution (middle) and wind speed variation distribution (right).



**Fig. 2.** Autumn campus session: measurement of the average wind speed distribution (left), maximum wind speed distribution (middle) and wind speed variation distribution (right).

From the average wind speed distribution map, the average point in spring is higher than that in autumn, and the average in spring and autumn is 0.3–3 m/s. According to the literature, the wind speed less than 0.4 m/s will affect the diffusion of air pollutants. It is found that the average wind speeds of all the points are above 0.55 m/s in spring, but there are three points (0a, 2b and 7b) in autumn with an average wind speed of 0.3–0.4 m/s, which implies a risk of certain pollutants gathering. Considering that the wind comfort is poor under the condition of 0.6 m/s, there may be still a certain sense of wind discomfort in these points. According to the zone of 1–5 m/s as the general comfortable wind speed standard, we found that all the points on the campus meet the requirements, and the overall wind environment is good.

According to the statistical radar chart of the highest wind frequency and the spring and autumn of different measuring points, it is found that the main wind direction in the spring is northeast and southwest, and the main wind direction in autumn is northwest and southwest. Generally, spring wind is more complex and changeable than wind in autumn. The overall wind corridor in campus at the pedestrian height is suggested to locate in the southwest to the north. According to the maximum wind speed distribution map, there are some points (spring: 5a, 6', 7', 3c', 2d and 6d; autumn: 2c and 2d) that reach a very uncomfortable wind speed zone of 10 m/s, which should be taken protective measures. These points are mainly distributed around the high-rise buildings and have a certain open space. According to the magnitude of wind speed change, the wind speed change of most points is between 40%–80%. At the same time, most of the points in spring have changes larger than that of autumn, but the points

with changes greater than 120% in autumn are more than that in spring. Overall, the points with larger changes are mainly located in the surrounding area of the campus.

In addition, in order to better discover the law and analyze the wind environment of the campus, we have the average wind speed and change interval, the average maximum wind speed and the change interval, the average variation range and percentage of the instantaneous wind speed in the spring, autumn and the two seasons together. The wind comfort zones area, wind shadow area, static wind area and wind disaster point were also analyzed, mainly through the frequency ratio of the instantaneous wind speed of each measuring point appearing in a certain interval, as shown in Table 1.

**Table 1.** Analysis of measured wind environment in each season.

	Av. wind speed (m/s)	Av. wind speed interval (m/s)	Av. max. wind speed (m/s)	Max. wind speed interval (m/s)	Av. wind speed change (%)	Pct. of comfortable wind measures (%)	Pct. of wind shadow measures (%)	Pct. of static wind measures (%)	Risky wind points	Av. Ratio of risky wind of each point (%)
Spring	1.38	0.1–5.7	2.58	0.4–9.5	59.9	51.6	40.8	9	2	0.8
Autumn	0.87	0.02–4.2	1.5	0.3–6.6	67.4	29.9	57.4	19.6	0	0
Av.	1.13	0.04–4.8	2.04	0.3–7.9	67.6	40.4	53.9	16		

Note: Magnitude of change: standard deviation of wind speed change/average wind speed; Wind comfort point ratio: the ratio of the instantaneous wind speed in the 1 ~ 5 m/s area point frequency to the total measurement frequency of the total evaluation point; Wind shadow area point ratio: instantaneous wind speed less than 1m/s area point frequency ratio of the total evaluation point of the total measurement frequency; Static wind point ratio: instantaneous wind speed is less than 0.3 m/s area point frequency ratio of the total evaluation point of the total measurement frequency; Average potential wind danger rate: the ratio of the frequency of the instantaneous wind speed at the wind disaster point greater than 15 m/s to the total frequency of the wind disaster point.

It can be seen from the table that the average wind speed and the average maximum wind speed in spring are both larger than those in autumn, and the overall variation range of average and maximum wind speed are also larger; However, the wind speed changes at specific points are larger in autumn, indicating that the average wind speed change is larger than that of spring. The overall wind average velocity is less than 1 m/s in autumn, which indicates discomfort for wind environment. Generally, the frequency of wind comfort zone measurement is not high (only 40%), and the percentage of comfortable points in spring is higher than that in autumn, though it is only half of the instantaneous wind speed is between 1–5 m/s. On the other hand, the wind shadow area and the static wind area in autumn are generally larger than those in spring. Especially in the static wind zone, the instantaneous wind speed in the autumn measuring point accounts for nearly 20%, which has greater discomfort and risk of pollutant accumulation. However, for wind danger with instantaneous wind speeds greater than 15 m/s, only one point each day (5a and 6') were found in two days of spring, with potential wind danger rates 0.6% and 1% respectively, which surpass the dangerous wind environment standards (0.05%) and thus special attention for these two points is required.

#### 4. CFD simulation analysis

In addition to the above routine field measurements, we also carried out CFD numerical simulation to evaluate the campus wind environment without blind spots. In this experiment, the ANSYS14.0 platform FLUENT is used for iterative operation, and the k-ε standard turbulence model is selected. The most of the parameter settings can be see the reference of Wang et al. [9]. The initial wind condition is  $U = U_0(Z / Z_0)^\alpha$  (where the reference wind speed  $U_0 = 3$  m/s, with reference height  $Z_0 = 10$  m and roughness coefficient  $\alpha = 0.3$ ), a three-dimensional model of the campus (including surrounding buildings less than 200 m away). Eight wind inlet directions in 360° with an interval of 45° with uniform wind environment condition are considered. Each scenarios result is shown in Fig. 3.

In order to compare CFD results and site measurement, we made a superimposition of the different scenarios with their corresponding transparency percentage according to the wind frequency weight in the annual wind rose diagram provided by the campus weather station (see Fig. 4b). Therefore the overall average wind environment map of the campus can be superimposed and compared with the on-site measured spring and autumn comprehensive average wind environment map (Fig. 5). Wind speed values comparison of each point is shown in Fig. 6.

From the Figs. 5–6, we can find that the CFD simulation result has much similarity with the site measurement: most points has an average wind speed less than 3 m/s, points with high wind speeds (e.g., 1, 2, 5a, 1d and 6d) show

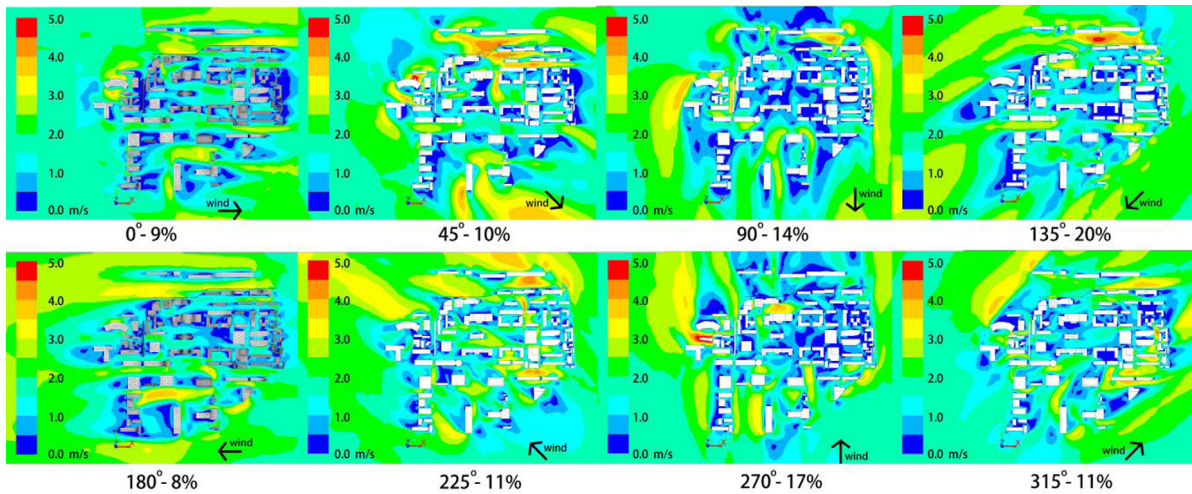


Fig. 3. Wind velocity profile simulation results under different wind inlet direction.

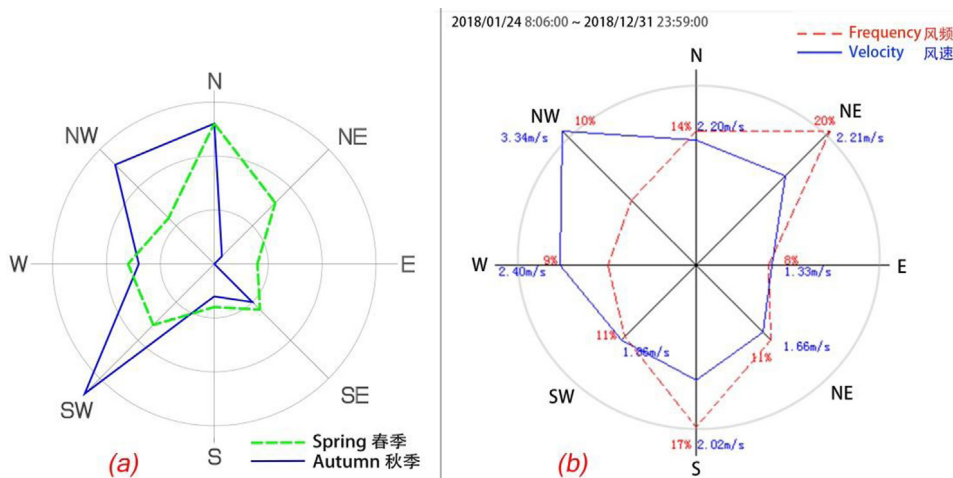


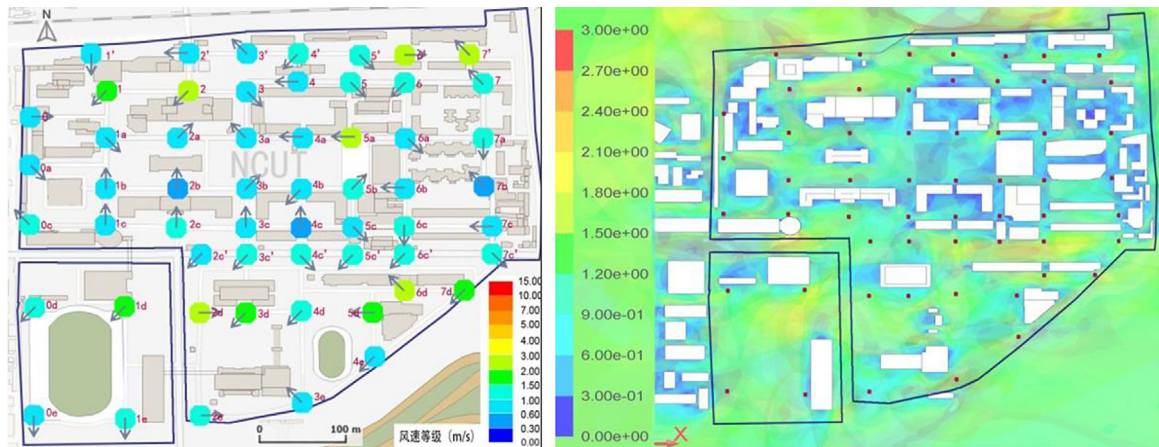
Fig. 4. (a) wind rose distribution from on-site measurement in the campus (measurement height  $Z = 2$  m), (b) wind rose distribution from data of meteorology station on top of roof ( $Z = 60$  m).

much correlation between the two methods. However, there are still some points (e.g. 2b, 4c', 5c', 6c') showing perceptible differences. Here, with the help of numerical simulation, we can find out those wind risky points and especially the statistic wind position in the campus. According to the close quantitative comparison (Fig. 6), we can see that the average wind speed of total points for on-site measurement is 1.15 m/s, and the total average wind speed for numerical simulation is 1.14 m/s. The general average difference between results of the two methods is around 37%, evened by differences of every measuring point.

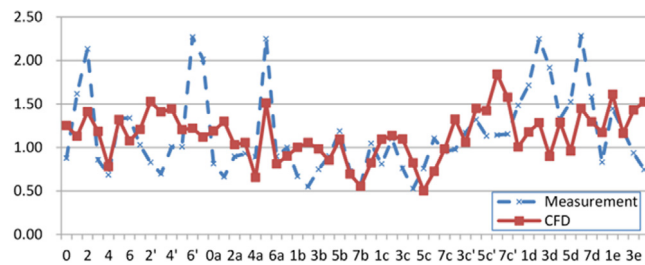
Concerning the difference of the two methods, we may as well find the difference in wind rose distributions from data of campus wind measurement at pedestrian level and data of weather station installed over roof (Fig. 4). It should be noted that here the measurement data, limited to autumn–spring data, can never be the same with the annual one, but the initial condition and wind rose used for CFD simulation is annual data. Therefore a certain inaccuracy is caused by the insufficient sample of on-site measurement.

### 5. Campus wind energy potential

Apart from pedestrian level wind environment analysis, CFD simulation can also evaluate wind energy potential at a high altitude, for example, over roof of some high-rise building. In campus of NCUT, we find three high-rise



**Fig. 5.** Measurement of the average campus wind height average wind speed distribution (left), numerical simulation wind average speed with local wind distribution (right).



**Fig. 6.** Wind speed comparison between measurement and numerical simulation of each point.

buildings: Haoxue building, Hanxue building and Boyuan building. Their roof heights and plan area are given, as show in the simulation 3D model of the campus (Fig. 7). Floor plan zones at 6 m and 10 m over these three buildings' roofs were selected as wind energy evaluation area. With assistant of UDF (User define function), we can get the weighted wind velocity cubical value by integrated area of the evaluation zones. Then the deductive averaged wind velocity of each zone in different wind inlet session can be found (Table 2).

In brief, we can see that the averaged values of each inlet direction are mostly bigger than 3 m/s, which is favorable condition for wind energy exploitation. As for the evaluation height above roof, there is much variety for these three building: Boyuan building has big difference between the case of 6 m and 10 m, while Haoxue building has very few gap between the two cases. Apart from wind velocity value, exploitable roof area is another important aspect for developing wind energy potential over roof, as it will influence the number of actual wind turbines which can be installed.

**Table 2.** Weighted wind velocity of different level over roof of the three buildings (m/s).

	Wind inlet directions (°)								Av. of each direction
	0	45	90	135	180	225	270	315	
Bo6m	2.54	4.42	2.08	2.48	1.42	2.07	3.01	2.14	2.546
Bo10m	3.69	5.31	2.61	2.84	1.97	2.53	4.30	2.59	3.248
Han6m	3.25	3.69	2.84	3.39	1.73	2.80	4.11	1.43	3.039
Han10m	3.78	4.00	3.39	3.55	2.00	2.92	4.72	1.70	3.395
Hao6m	3.94	5.36	3.30	3.11	1.84	2.88	5.51	2.45	3.644
Hao10m	4.16	5.36	3.54	3.37	1.96	2.88	5.48	2.58	3.770

Note: Bo means Boyuan building, Han means Hanxue building, Hao means Haoxue building.

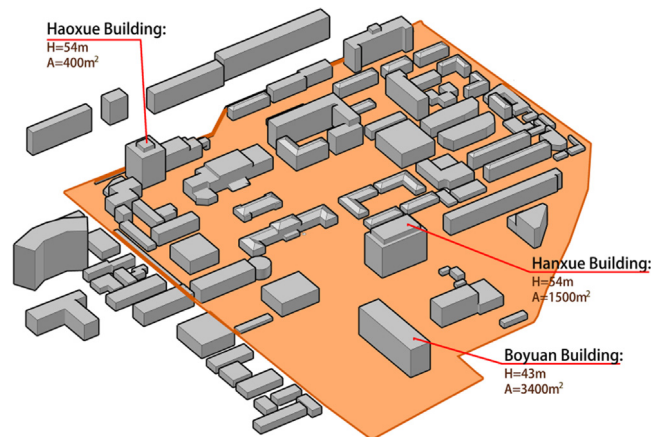


Fig. 7. Potential buildings of the campus.

## 6. Conclusion

This paper carried out a general survey and analysis of the wind environment of the main traffic nodes of North China University of Technology through the multi-day measurement of 57 points in the spring and autumn. For the part of pedestrian level, the results show that the overall wind environment of the campus is fair: the average wind speed is between 0.04–4.8 m/s, the average wind speed in spring (1.38 m/s) is slightly larger than that in autumn (0.87 m/s), and the wind direction changes at each measuring point are more complicated. In the spring campus, there are some high wind speeds or dangers. Some parts of the autumn campus are in the static wind zone where there is a risk of pollutant accumulation. The overall frequency of campus wind comfort location measurement is not high, 52% and 30% in spring and autumn respectively. It is necessary to elaborate the landscape environment and create a better campus physical environment.

Apart from on-site measurement, CFD simulation was undertaken in order to evaluate wind environment of the whole campus and at different height. Three high-rise buildings were chosen to evaluate wind performance over their roofs. The results of CFD simulation show that the averaged wind velocity values are mostly bigger than 3 m/s (at 6 m or 10 m above roof), which is favorable condition for wind energy exploitation. However, further detailed evaluation is needed for the wind turbine installation position as there is much varieties on the evaluation level, building roof area and velocity distribution of each building.

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