Simplified Spatial Wind Vector Interpolation Method for Airport Runway Orientation Analysis

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Abstract. Runway orientation, guided by windrose analysis, is crucial in airport planning as it directly influences aircraft performance and airport capacity. Proper alignment reduces crosswind components during takeoff and landing, ensuring safer operations and increase runway coverage. For a new airport in a location where comprehensive historical wind data is not available, prediction methods become an invaluable tool. To address this issue, this paper proposes a simplified interpolation method to predict wind data at target location based on available data from surrounding climate station readings. This paper validates the proposed method through a comparative analysis of predicted and actual windrose and its subsequent runway coverage at two prominent currently operational Indonesian airports: Soekarno Hatta International Airport in Cengkareng (CGK) and Sultan Hasanuddin International Airport in Ujung Pandang (UPG). Additionally, the study employs the proposed method to determine the optimal runway orientation for a new VVIP airport in Indonesia's new capital city (IKN), Nusantara. The analysis reveals that the proposed interpolation method yields runway heading recommendations closely aligned with those derived from actual wind data, both for the case of CGK and UPG airport. The proposed method recommends optimal runway heading between 03-21 and 08-26 for new VVIP Airport at Nusantara, new capital city of Indonesia (IKN).

1 Introduction

Runway orientation, guided by windrose analysis, is pivotal in airport planning as it ensures the safety, efficiency, and sustainability of airport operations. It directly influences aircraft performance, capacity, noise levels, and environmental considerations, making it a fundamental aspect of airport design and management. Aircraft take off and land into the wind whenever possible to maximize control and lift. Windrose analysis helps determine the prevailing wind directions at the airport site, enabling planners to align runways accordingly. Proper alignment reduces crosswind and tailwind components during takeoff and landing, ensuring safer operations. Efficient runway orientation contributes to the overall capacity of the airport. By minimizing crosswind-related delays and ensuring safe takeoff and landing conditions, airports can handle a higher volume of aircraft movements, supporting the growing demand for air travel.

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For a new airport in a location where comprehensive historical wind data is not readily available, prediction methods become an invaluable tool in the planning and design process. To address this issue, this paper proposes a simplified method to predict wind data based on available data from surrounding climate station readings. This method is expected to fill the need for practical solution during early feasibility study stage of airport planning. This paper validates the proposed method through a comparative analysis of predicted and actual historical wind data readings at two prominent currently operational Indonesian airports: Soekarno Hatta International Airport in Cengkareng (CGK) and Sultan Hasanuddin International Airport in Ujung Pandang (UPG). Additionally, the study employs the proposed method to determine the optimal runway orientation for a new presidential VVIP airport in Indonesia’s new capital city (IKN), Nusantara.

2 Wind Analysis in Airport Planning

The orientation and quantity of runways are determined, in part, by the influence of wind. It is optimal for a runway to be positioned in line with the predominant wind direction. Wind conditions have differing impacts on aircraft, with smaller planes generally experiencing a greater effect, especially when it comes to crosswind elements. Crosswinds frequently play a role in accidents involving smaller aircraft. Airport planners and designers must conduct a precise wind analysis to ensure the optimal runway orientation and quantity. Recent studies on windrose prediction method have been mostly driven by researchers in the area of renewable energy and environment. Lepore et.al [1] propose new statistical approach for site-specific wind potential evaluation within the Bayesian framework that only require collection of short-term data for use in wind-farm layout design. Damousis et.al [2] suggested a model that mixed the fuzzy method with spatial correlation. The study used data from places within 30 kilometers of each other and employed a genetic-based algorithm for training. The model was tested on both flat and complex terrains. Bilgili [3] applied ANN (Artificial Neural Network) principles to predict the mean monthly wind speed of any target station using the mean monthly wind speeds of neighboring stations. FAA (Federal Aviation Administration) suggest that for the purpose runway orientation planning, a record which covers the last 10 consecutive years of wind observations is preferred [4]. However, obtaining such historical data is often impractical or unavailable. Thus, require analysis method to predict wind speed and its dominant direction at airport candidate site location.

2.1 Interpolation of Wind Vector

Peter E. Thornton, Running, and White [5] suggested interpolating meteorological data using a truncated Gaussian filter. The method for interpolating wind vectors at a specific target point, denoted as \( p \), can be described as follows. Consider the wind vector at a given weather station \( i \) as \( v_i \). Initially, \( v_i \) is represented in polar coordinates, where we have the wind speed \( u_i \) and wind direction \( \theta_i \). If we convert \( v_i \) into Cartesian coordinates, it can be expressed as:

\[
x_i = u_i \cdot \sin \theta_i \quad y_i = u_i \cdot \cos \theta_i
\]

The predicted wind vector, denoted as \( v_p \), is calculated as the weighted mean of the wind vectors \( \{v_i\} \) for all points \( i = 1, ..., n \) predicted at location \( p \), with the weighting determined by the truncated Gaussian filter’s interpolation weights \( W_i \):

\[
x_p = \frac{\sum_{i=1}^{n} W_i \cdot x_i}{\sum_{i=1}^{n} W_i} \quad y_p = \frac{\sum_{i=1}^{n} W_i \cdot y_i}{\sum_{i=1}^{n} W_i}
\]
The polar coordinates for the predicted wind vector $v_p$ are as follows:

$$u_p = \sqrt{x_p^2 + y_p^2} ; \theta_p = \tan^{-1}\left(\frac{x_p}{y_p}\right)$$

The form of interpolation weight with respect to a central point $p$ is:

$$W(r) = e^{-\alpha \left(\frac{r}{R_p}\right)^2} - e^{-\alpha}$$

In this context, $r$ represents the radial distance from point $p$. $R_p$ stands for the truncation distance, and $\alpha$ denotes the shape parameter. When this filter is spatially convolved with a collection of weather station positions, it yields a vector of weights linked to observations for each specific target point. In this study, a straightforward interpolation weight form was introduced, where $W_i$ is the inverse of straight-line distance, $d_{ip}$ between the weather station $i$ and the target location $p$:

$$W_i = \frac{1}{d_{ip}}$$

Equation (1) then become:

$$x_p = \frac{\sum_{i=1}^{n} \frac{1}{d_{ip}} \cdot x_i}{\sum_{i=1}^{n} \frac{1}{d_{ip}}} ; y_p = \frac{\sum_{i=1}^{n} \frac{1}{d_{ip}} \cdot y_i}{\sum_{i=1}^{n} \frac{1}{d_{ip}}}$$

Using result from Equation (6), the wind vector at location $p$ can be calculated using Equation (3).

### 2.2 Runway Coverage

Runway coverage is the percentage of time crosswind components are above an acceptable velocity. FAA suggest that the configuration of runways at an aerodrome should be designed to ensure that the runway coverage for the specific aircraft it serves remains above 95 percent [4]. ICAO prescribed maximum acceptable crosswind component based on Aerodrome Reference Field Length (ARFL) as shown on Table 1 [6].

<table>
<thead>
<tr>
<th>ARFL class (m)</th>
<th>Max crosswind component, knots (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 1500</td>
<td>20 (10.3)</td>
</tr>
<tr>
<td>1200-1500</td>
<td>13 (6.7)</td>
</tr>
<tr>
<td>&lt;1200</td>
<td>10 (5.2)</td>
</tr>
</tbody>
</table>

The wind vector interpolation process would yield wind speed and wind direction frequency distribution through which the percentage of crosswind component can be determined. The crosswind component, $V_x$ of a runway with heading $\delta$ given wind direction $\theta$ is calculated using Equation (7).

$$V_x = v \sin(\delta - \theta)$$
Where \( \theta \) is the relative angle between runway heading and wind direction. The percentage of crosswind component exceeding maximum requirement can be calculated given the frequency distribution of wind speed and wind direction from interpolation process. Examples illustrating the application of wind analysis for determining runway coverage based on a given dataset can be found in [7] [8] [9].

2.3 Previous Studies in Indonesia


3 Methods

3.1 Research activities

The study comprised two primary components as illustrated in Fig. 1: 1) A comparative analysis of predicted versus observed windrose at an operational airport, and 2) Application of the proposed methodology to evaluate its suitability for a potential new airport location. The dataset utilized for this study consisted of ten years (2012-2022) of historical maximum daily wind data and its corresponding direction obtained from climates stations administered by the Indonesian Meteorological, Climatological, and Geophysical Agency (BMKG). The research concluded with a thorough examination of the findings, including estimations of runway coverage based on both projected and observed wind vectors.

3.2 Analysis procedure

Prediction of wind vectors at target location \( p \) and the analysis procedure for runway coverage analysis is shown in Fig. 2. The windrose is developed using freely available \textit{WrpPlot} computer program [13]. This study uses 36 wind quadrant system as suggested by FAA for wind rose analysis.

3.3 Study case airport

3.3.1 Soekarno-Hatta International Airport (CGK)

Soekarno-Hatta International Airport (CGK), situated in Tangerang, Banten, plays a pivotal role as a major hub for domestic flights within Indonesia. Currently the airport is operating with three parallel runways heading 07-25, each with a length ranging from 3000 to 3700 meters, enabling it to accommodate the operations of wide-body aircraft, including B777s and A330s. Two climate reading stations administered by BMKG (Indonesian Meteorological, Climatological, and Geophysical Agency) are chosen to predict wind vector in CGK in this study: Banten Climate Station, positioned 19 kilometers southeast of CGK, and Tanjung Priok Climate Station, situated 26 kilometers to the east.

3.3.2 Ujung Pandang Makassar International Airport (UPG)

Ujung Pandang Makassar Airport (UPG), situated in Makassar, South Sulawesi, serves as a major hub for domestic flights in the eastern region of Indonesia. This airport has been

![Fig. 1 Research activities](image-url)
by the Indonesian Meteorological, Climatological, and Geophysical Agency (BMKG). This data was collected from climate stations located in proximity to CGK, UPG, and the prospective site for the new VVIP Presidential Airport. The research concluded with a thorough examination of the findings, including estimations of runway coverage based on both projected and observed wind vectors.

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Fig. 2 Proposed wind vector interpolation and runway coverage analysis procedure

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selected as a representative case study due to its unique runway configuration. At present, UPG boasts two runways configured in a V shape, oriented with headings 13-31 and 03-21, each with respective lengths of 2500 meters and 3000 meters. This V-shaped layout is believed to offer the airport enhanced wind coverage capabilities. To predict wind vectors at UPG for this research, data from the Paotere seaport climate station (located 15.2 meters to the southwest) and the South Sulawesi Climate Station (positioned 15.5 meters to the north) are utilized.

3.3.3 Indonesia New Capital VVIP Presidential Airport

The Indonesian government had announced plans to relocate the capital city from Jakarta to a new site. Plans for a new Very Very Important Person (VVIP) airport were part of the broader development strategy for Indonesia’s new capital city. The new VVIP airport is planned to be located in Penajam Paser Utara, approximately 25 km to the northwest of Balikpapan. In this study, the orientation of the new VVIP aiport runway is predicted using proposed method by utilizing data from Sepinggan airport climate station (25 km-southeast) and Samarinda climate station (94 km-Northeast).

4 Results

4.1 Predicted vs actual windrose

Fig. 3 and Fig. 4 displays the graphical windrose generated from actual and predicted value at CGK. As expected, there is a difference in the resulting windrose. Plot of both actual and predicted wind speed and direction along line of equality show fair correlation between the two quantities as shown on Fig. 5.

![Fig. 3 CGK Windrose generated using actual wind data from CGK airport climate station](image-url)
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Fig. 4 CGK Windrose generated using wind data interpolated from neighbouring climate station

$$R^2=0.75$$

$$R^2=0.8476$$

Fig. 5 Plot of predicted and observed wind direction (left) and wind speed (right) along line of equality_CGK airport

Fig. 6 Actual vs predicted wind speed frequency distribution_CGK

$$\%$$

Actual windrose_CGK  Predicted windrose_CGK
In terms of wind speed distribution, the observed data from the CGK climate station, as depicted in Fig. 6, exhibits a higher frequency of high wind speeds. This is well understood since CGK is located near coastal area where wind is expected to be stronger compared to inland area [14] [15]. Utilizing a neighboring station located within a similar geographical feature would possibly enhance the accuracy of wind speed predictions. To facilitate this, future research endeavors should focus on identifying the pertinent geographical variables to consider when choosing neighboring climate stations for wind rose predictions at specific target locations. As for wind direction distribution, the actual data at CGK shows rather similar pattern compared to predicted value as shown on Fig. 7.

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![Fig. 7 Actual vs predicted wind heading frequency distribution CGK](image)

**Fig. 7** Actual vs predicted wind heading frequency distribution CGK

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![Fig. 8 UPG Windrose generated using actual wind data from UPG airport climate station](image)

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As for wind direction distribution, the actual data at CGK shows rather similar patterns compared to predicted values as shown in Fig. 7. Fig. 8 and Fig. 9 display the graphical windrose generated from actual and predicted values at UPG. Compared to CGK, the resulting predicted vs actual windrose at UPG is relatively more similar. Plot of both actual and predicted wind speed and direction along line of equality show good correlation between the two quantities as shown on Fig. 10.

Wind speed distribution based on actual wind data at UPG exhibits higher frequency of lower wind speed compared to predicted value as shown on Fig. 11. Compared to CGK, UPG is located in an inland area where the wind speed is expected to be relatively lower. The utilization of wind data from the Paotere seaport climate station in the prediction process could potentially account for the higher frequency of high wind speeds observed in the resulting predictions for wind speed. The predicted vs actual frequency distribution of wind direction at UPG show strong similarity as shown in Fig. 12.
Fig. 11 Actual vs predicted wind speed frequency distribution_UPG

4.2 Runway Coverage

Fig. 14 and Fig. 16 show the analysis of runway coverage determined based on actual and predicted wind rose at CGK and UPG, respectively. The analysis reveals that employing the predicted wind rose at CGK results in a nearly identical runway coverage pattern compared to that derived from the actual wind rose, especially evident in ARFL class > 1500, as illustrated in Fig. 14a and Fig. 14b. On the other hand, using the actual wind rose for runway coverage at CGK yields a more conservative runway coverage value, particularly for ARFL classes of 1200-1500 and < 1200.

The congruence in predicted and actual runway coverage is similarly observed at UPG. Furthermore, the analysis highlights that at UPG, runway 13-31 exhibits higher runway coverage compared to runway 03-21, particularly for aircraft operations within ARFL Class < 1200. Notably, despite its orientation perpendicular to the prevailing wind directions, the coverage of UPG's runway 03-21 for ARFL class > 1500 still consistently exceeds 95%. This is attributable to the fact that the crosswind component generally remains below the maximum allowable value for this specific ARFL class. This finding marks the importance of runway wind rose analysis as it allows airport operators to assess the degree of flexibility in choosing runway headings.
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The analysis result from CGK and UPG provide certain degree of certainty of the proposed interpolation method as it reveals similar runway coverage based on actual and predicted windrose. Using the same method, the windrose at Indonesia new capital VVIP airport site location is generated as shown in Fig. 17. Similarly, the resulting runway coverage for all possible runway heading is shown in Fig. 18. The analysis shows that the optimal runway heading for the new VVIP airport is within range of 03-21 and 07-25.

**Fig. 15** Runway coverage for various runway heading at UPG using Predicted (a) and Actual (b) windrose

**Fig. 16** Recapitulation of existing UPG runway coverage for runway 03-21 (a) and runway 13-31 (b) using both actual and predicted data, UPG runway heading layout (c)

**Conclusion**

This study introduces a simplified interpolation method for wind rose prediction in the context of runway orientation analysis. The analysis demonstrates a negligible disparity between the actual and predicted wind roses generated using this proposed method. Furthermore, it can be concluded that employing the predicted windrose would yield nearly indistinguishable runway coverage values, particularly for ARFL class > 1500. Utilizing this method, our study recommends an optimal runway heading for Indonesia’s new capital VVIP airport within the range of 03-21 and 07-25.
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Future investigations should aim to enhance the prediction model while maintaining its simplicity and accuracy. This entails research to identify key geographical variables when selecting neighboring climate stations for wind rose predictions at specific target locations. Additionally, developing a closed-form equation to predict wind vectors that incorporates other meteorological parameters such as temperature and humidity is crucial. These advanced models should ideally provide highly accurate predictions without sacrificing the ease of analysis.

6 References

Runway coverage for various runway heading at IKN VVIP airport site

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References


