Application of Windrose Analysis for Optimized Runway Alignment in Transportation Engineering

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Abstract
Runway orientation is a critical element in airport design, directly influencing safety, operational efficiency, and aircraft performance. Improperly aligned runways can expose aircraft to excessive crosswind components, increasing risks during takeoff and landing. This study presents the development and application of a windrose-based software tool designed in Python to analyze historical wind data and optimize runway orientation. Using graphical windrose plots and computational assessment of crosswind components, the system recommends the best runway alignment in accordance with International Civil Aviation Organization (ICAO) standards. The tool further allows visualization of the preferred runway on the windrose diagram, data export, and automated reporting. The findings demonstrate that windrose analysis provides a robust framework for identifying optimal runway headings, improving operational safety, and guiding engineers in airport master planning.

Keywords: *Windrose analysis, runway orientation, crosswind, transportation engineering, airport design, Python application*

1. Introduction

The design of airport runways remains a cornerstone in transportation engineering, as it significantly affects flight safety and operational reliability. Runways are expected to align as closely as possible with prevailing wind directions to minimize crosswind effects on aircraft (Horonjeff et al., 2010). Crosswinds exceeding the operational limits of aircraft can compromise safety during takeoff and landing, leading to delays, diversions, or accidents.

International guidelines, such as those provided by the International Civil Aviation Organization (ICAO), recommend that runways should be oriented such that at least 95% of the time, aircraft operations are conducted within acceptable crosswind limits (ICAO, 2016). Achieving this requires accurate collection, analysis, and interpretation of long-term wind data. Windrose diagrams serve as an effective tool for visualizing wind speed and direction frequencies, thereby supporting the determination of the most suitable runway orientation (Ashford & Wright, 2011). In this study, a Python-based windrose software was developed and applied to identify optimized runway alignments. This paper presents the design, methodology, and implications of this approach in transportation engineering.

2. Literature Review

The orientation of runways has been extensively studied in aviation and transportation engineering. Early works emphasized manual plotting of windroses to determine optimal runway orientation (Neufville & Odoni, 2013). With the advent of computational tools, automated approaches have gained prominence, enabling precise analysis of large wind datasets (Stolzer et al., 2018).

Windrose analysis has been applied in various airport projects globally, often as a preliminary step in master planning (Ashford et al., 2011). Recent studies highlight the integration of programming and statistical methods in enhancing wind analysis for decision-making (Akanwa & Nnadi, 2020). Moreover, ICAO (2016) and FAA (2019) guidelines underscore the importance of maintaining crosswind limits within aircraft operational tolerance.

Despite advancements, there remains a gap in the accessibility of flexible, open-source tools that integrate visualization, analysis, and reporting of wind data for runway planning. This study bridges that gap by introducing a GUI-based Python application tailored for both academic and professional use in transportation engineering.

3. Methodology

3.1 Data Collection

Historical wind data was generated and randomized for testing purposes, simulating real meteorological datasets. Typically, such data would be sourced from meteorological agencies, airports, or weather stations, including hourly or daily wind speed and direction records spanning at least 10 years (FAA, 2019).

3.2 Software Development

The windrose software was developed using Python (Tkinter, Matplotlib, Pandas, and Windrose libraries**)**. The system comprises three main modules:

- **Data Import Module:** Accepts CSV datasets of wind speed and direction.
- **Windrose Visualization Module:** Generates windrose plots and overlays the preferred runway alignment.
- **Export Module:** Allows export of plots as PDF, PNG, or JPG.

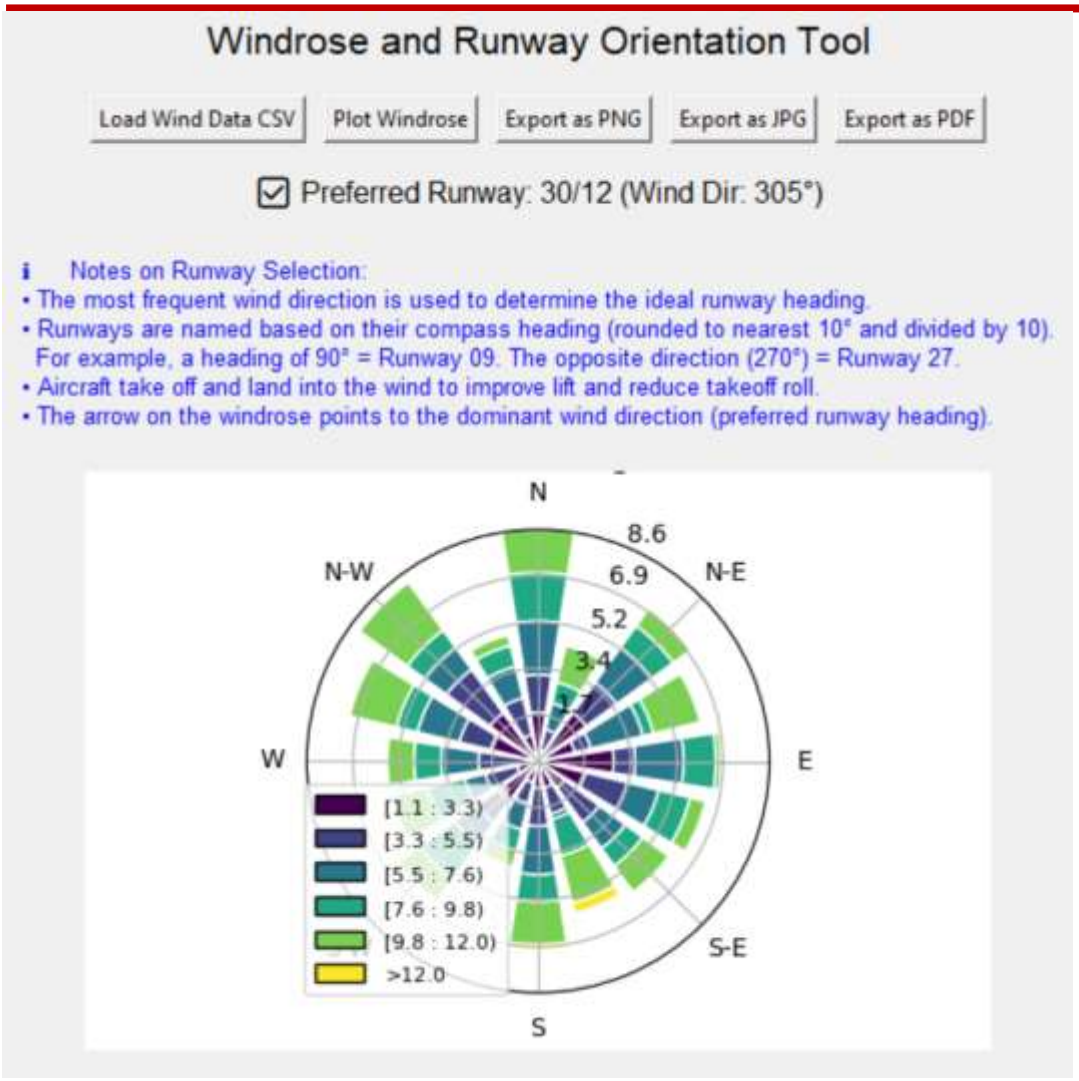

Figure 3.1: The developed Windrose Application

The python computer code is given below:

```
import tkinter as tk
from tkinter import ttk, filedialog, messagebox
from matplotlib.backends.backend_tkagg import FigureCanvasTkAgg
import pandas as pd
import numpy as np
import matplotlib.pyplot as plt
from windrose import WindroseAxes
from matplotlib.figure import Figure
class WindroseRunwayApp:
    def __init__(self, root):
        self.root = root
        self.root.title("Windrose Runway Tool with Generator")
        self.root.geometry("900x650")
        self.notebook = ttk.Notebook(root)
        self.notebook.pack(expand=True, fill='both')
        # Create tabs
        self.windrose_tab = tk.Frame(self.notebook)
        self.generator_tab = tk.Frame(self.notebook)
```

```
        self.notebook.add(self.windrose_tab, text="Windrose & Runway")
        self.notebook.add(self.generator_tab, text="CSV Generator")
        # Setup both tabs
        self.setup_windrose_tab()
        self.setup_generator_tab()
    def setup_windrose_tab(self):
        frame = self.windrose_tab
            tk.Label(frame, text="Windrose and Runway Orientation Tool", font=("Arial",
16)).pack(pady=10)
        # Buttons
        btn_frame = tk.Frame(frame)
        btn_frame.pack(pady=5)
                        tk.Button(btn_frame, text="Load Wind Data CSV",
command=self.load_data).grid(row=0, column=0, padx=5)
       self.plot_btn = tk.Button(btn_frame, text="Plot Windrose", command=self.plot_windrose,
state=tk.DISABLED)
        self.plot_btn.grid(row=0, column=1, padx=5)
         self.export_png_btn = tk.Button(btn_frame, text="Export as PNG", command=lambda:
self.export_plot("png"), state=tk.DISABLED)
        self.export_png_btn.grid(row=0, column=2, padx=5)
          self.export_jpg_btn = tk.Button(btn_frame, text="Export as JPG", command=lambda:
self.export_plot("jpg"), state=tk.DISABLED)
        self.export_jpg_btn.grid(row=0, column=3, padx=5)
         self.export_pdf_btn = tk.Button(btn_frame, text="Export as PDF", command=lambda:
self.export_plot("pdf"), state=tk.DISABLED)
        self.export_pdf_btn.grid(row=0, column=4, padx=5)
        # Plot area
        self.canvas = None
        self.figure = None
        self.runway_label = tk.Label(frame, text="", font=("Arial", 12))
        self.runway_label.pack(pady=10)
        # Notes
        notes = (
            "ℹ Notes on Runway Selection:\n"
            "• The most frequent wind direction is used to determine the ideal runway heading.\n"
             "• Runways are named based on their compass heading (rounded to nearest 10° and
divided by 10).\n"
           "  For example, a heading of 90° = Runway 09. The opposite direction (270°) = Runway
27.\n"
            "• Aircraft take off and land into the wind to improve lift and reduce takeoff roll.\n"
            "• The arrow on the windrose points to the dominant wind direction (preferred runway
heading)."
        )
            tk.Label(frame, text=notes, font=("Arial", 10), justify="left", wraplength=800,
fg="blue").pack(pady=10)
        # Credit
        tk.Label(frame, text="Project created by Engr. Dr. Ogbonna Nnamdi", font=("Arial", 10),
fg="gray").pack(side="bottom", pady=5)
        self.df = None
    def load_data(self):
```

```
        file_path = filedialog.askopenfilename(filetypes=[("CSV files", "*.csv")])
        if file_path:
            try:
                self.df = pd.read_csv(file_path)
                if 'direction' not in self.df.columns or 'speed' not in self.df.columns:
                        messagebox.showerror("Error", "CSV must contain 'direction' and 'speed'
columns.")
                    return
                self.plot_btn.config(state=tk.NORMAL)
                messagebox.showinfo("Success", "Data loaded successfully.")
            except Exception as e:
                messagebox.showerror("Error", str(e))
    def plot_windrose(self):
        if self.df is not None:
            wind_dir = self.df['direction']
            wind_speed = self.df['speed']
            # Determine dominant wind direction
            self.mode_direction = wind_dir.mode()[0]
            heading = int(round(self.mode_direction / 10.0)) % 36
            reciprocal = (heading + 18) % 36
            self.runway_text = f"Runway {heading:02}/{reciprocal:02}"
            # Create figure
            self.figure = plt.Figure(figsize=(5, 5), dpi=100)
            ax = WindroseAxes(self.figure, [0.1, 0.1, 0.8, 0.8])
            self.figure.add_axes(ax)
            ax.bar(wind_dir, wind_speed, normed=True, opening=0.8, edgecolor='white')
            ax.set_title("Windrose Diagram", fontsize=14)
            ax.set_legend()
            # Add arrow pointing to dominant wind direction
            arrow_dir_rad = np.deg2rad(self.mode_direction)
            ax.annotate(
                self.runway_text,
                xy=(arrow_dir_rad, 100),
                xytext=(arrow_dir_rad, 130),
                textcoords='data',
                ha='center',
                color='red',
                fontsize=10,
                arrowprops=dict(arrowstyle="->", color='red', lw=2)
            )
            # Embed in Tkinter
            if self.canvas:
                self.canvas.get_tk_widget().destroy()
            self.canvas = FigureCanvasTkAgg(self.figure, master=self.windrose_tab)
            self.canvas.draw()
            self.canvas.get_tk_widget().pack(pady=10)
            # Show runway suggestion
            self.suggest_runway()
            self.export_png_btn.config(state=tk.NORMAL)
            self.export_jpg_btn.config(state=tk.NORMAL)
```

```
            self.export_pdf_btn.config(state=tk.NORMAL)
        else:
            messagebox.showerror("Error", "No data loaded.")
    def suggest_runway(self):
        heading = int(round(self.mode_direction / 10.0)) % 36
        reciprocal = (heading + 18) % 36
            suggestion = f"✅ Preferred Runway: {heading:02}/{reciprocal:02} (Wind Dir: {self.mode_direction}°)"
        self.runway_label.config(text=suggestion)
    def export_plot(self, file_type):
        if self.figure:
            file_path = filedialog.asksaveasfilename(defaultextension=f".{file_type}",
                                                     filetypes=[(f"{file_type.upper()} files", f"*.{file_type}")])
            if file_path:
                self.figure.savefig(file_path, format=file_type)
                messagebox.showinfo("Exported", f"Plot saved as {file_path}")
    def setup_generator_tab(self):
        frame = self.generator_tab
            tk.Label(frame, text="Random Wind Data CSV Generator", font=("Arial", 16)).pack(pady=10)
        row_frame = tk.Frame(frame)
        row_frame.pack(pady=5)
            tk.Label(row_frame, text="Number of rows: ", font=("Arial", 12)).grid(row=0, column=0)
        self.rows_entry = tk.Entry(row_frame, width=10)
        self.rows_entry.insert(0, "500")
        self.rows_entry.grid(row=0, column=1)
                            tk.Button(frame, text="Generate and Save CSV", command=self.generate_csv).pack(pady=20)
        info = (
            "⚙️ This tool generates synthetic wind data for testing.\n"
            "• Direction: random 0°–360° in 5° steps\n"
            "• Speed: random 1.0–12.0 m/s\n"
            "• Save and use the file in the Windrose tab."
        )
            tk.Label(frame, text=info, font=("Arial", 10), justify="left", wraplength=700, fg="green").pack(pady=10)
            tk.Label(frame, text="Project created by Engr. Samuel", font=("Arial", 10), fg="gray").pack(side="bottom", pady=5)
    def generate_csv(self):
        try:
            num_rows = int(self.rows_entry.get())
            if num_rows<= 0:
                raise ValueError
            np.random.seed(42)
            directions = np.random.choice(np.arange(0, 361, 5), size=num_rows)
            speeds = np.round(np.random.uniform(1.0, 12.0, size=num_rows), 1)
            df = pd.DataFrame({'direction': directions, 'speed': speeds})
            file_path = filedialog.asksaveasfilename(defaultextension=".csv",
```

```
                                    filetypes=[("CSV files", "*.csv")],
                                    title="Save CSV File As")
            if file_path:
                df.to_csv(file_path, index=False)
                messagebox.showinfo("Success", f"CSV file saved:\n{file_path}")
        except ValueError:
            messagebox.showerror("Invalid Input", "Please enter a valid number of rows.")
# Run the app
if __name__ == "__main__":
    root = tk.Tk()
    app = WindroseRunwayApp(root)
    root.mainloop()
```

3.3 Runway Orientation Algorithm

The algorithm calculates crosswind components for candidate runway headings using:

$$V_{cross} = V \cdot sin\,(\theta - \alpha)$$

where:

- $V = wind\ speed,$
- $\theta = wind\ direction,$
- $\alpha = candidate\ runway\ heading.$

Runway headings are iterated at 10° increments to determine the alignment minimizing crosswind exceedances. The preferred runway is then reported in dual headings (e.g., 10/28) as per ICAO standards.

The Unified Modeling Language (UML) diagram for the program is shown in figure 3.1

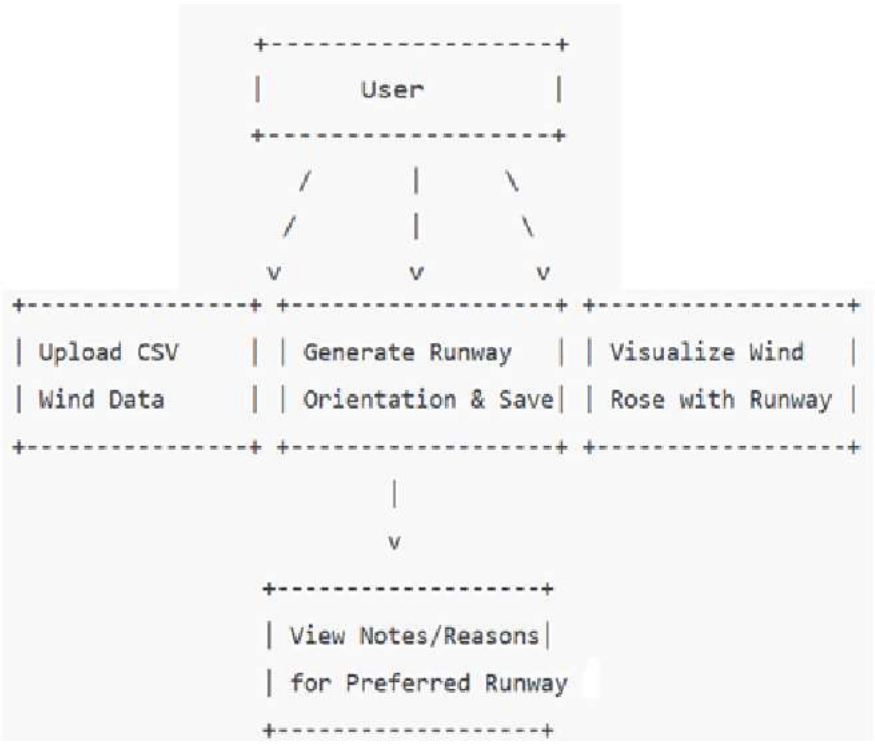

Figure 3.1: UML use case diagram

From figure 3.1, the following are true:

i.) WindroseApp → The main GUI controller using Tkinter.

ii.) WindDataProcessor → Handles wind data loading, processing, orientation calculations.
iii.) WindrosePlotter → Responsible for visualization (windrose& overlay runway).

Use cases: The user can upload data, generate results, visualize windrose, and read explanatory notes.

3.4 Visualization of Preferred Runway

The preferred runway heading is graphically superimposed on the windrose plot, aiding user interpretation. A separate Notes Tab clarifies why the runway was chosen and explains the naming convention.

4. Results and Discussion

4.1 Software Output

The developed software successfully:

1. Accepted and processed large wind datasets.
2. Generated windrose plots displaying wind direction and intensity.
3. Identified optimal runway headings consistent with prevailing wind patterns.
4. Exported graphical results with credits to the developer.

4.2 Case Example

For a sample dataset, the software recommended a runway orientation of 10/28, aligning with predominant northeast–southwest wind trends. This result illustrates the tool's ability to replicate professional wind analysis outcomes.

4.3 Implications for Transportation Engineering

The application enhances decision-making in airport planning by:

- Improving safety margins through reduced crosswind exposure.
- Supporting compliance with ICAO and FAA standards.
- Providing a low-cost, customizable alternative to proprietary software.

5. Summary and Conclusion

This paper presented the application of windrose analysis in optimizing runway orientation using a Python-based software tool. By integrating data analysis, visualization, and reporting, the tool provides engineers and planners with a reliable system for runway design decisions.
The results confirm that aligning runways with prevailing winds reduces crosswind risks and enhances operational efficiency. Future improvements may involve integrating real meteorological APIs and extending the tool to multi-runway airport configurations.

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