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# Fuel Efficiency Comparison of PBN and ILS Approach Procedures at Sam Ratulangi Airport

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## Abstract

This study evaluates the efficiency of approach procedures at Sam Ratulangi International Airport-Manado by comparing Required Navigation Performance (RNP) under Performance-Based Navigation (PBN) with the Instrument Landing System (ILS) as a conventional procedure. A simulation using the BlueSky ATM Simulator was conducted with 30 aircraft instances for each approach, utilizing real-time FlightRadar24 speed data to ensure operational realism. The analysis focused on three key metrics: distance flown, time spent, and fuel consumption. Results show that implementing of PBN procedures reduces distance flown by 15%, flight time by 15% and fuel consumption by 14% compared to ILS, demonstrating improved operational efficiency. This research provides a quantitative assessment of PBN systems' effectiveness in optimizing approach procedures, supporting aviation sustainability, and reducing operational costs.

***Keywords**: PBN, ILS, Fuel Efficiency, BlueSky Simulation, FlightRadar24, Sam Ratulangi International Airport*

## Nomenclature

| | | |
|---|---|---|
| $n$ | = | Required sample size |
| $C$ | = | Confidence Level |
| $p$ | = | The estimated probability of occurrence |
| $FC$ | = | Fuel Consumption, kg |
| $Dist$ | = | Distance flown, km |
| $FBR$ | = | Fuel Burn Rate, kg/km/seat |
| $nS$ | = | Number of seats |

## 1. Introduction

The aviation industry faces one of its greatest challenges: managing the rapid growth of air transportation without aggravating the global climate crisis. Aircraft emissions, which increased 6.8 times from 1960 to 2018, are projected to triple by 2050 if no significant changes are made (Gossling et al., 2020). As the industry recovers to pre-pandemic levels, the surge in air traffic risks undermining decarbonization efforts unless sustainable innovations in air traffic management and navigation systems are adopted (Gudmundsson et al., 2021).

Air navigation plays a critical role in addressing these challenges by optimizing airspace and operational procedures to reduce greenhouse gas (GHG) emissions. The Global Air Navigation Plan (GANP) and its associated Aviation System Block Upgrades (ASBUs), developed by ICAO, aim to harmonize the global aviation sector, enhance capacity and improve environmental efficiency. By implementing the ASBU Block 0 and 1 module, the



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aviation industry is projected to achieve annual fuel savings of 167 to 307 kg per flight, corresponding to a reduction of 26.2 to 48.2 million tons of $CO_2$ by 2025. These measures highlight the importance of integrating Performance-Based Navigation (PBN) as a conceptual solution for improving airspace design and operational efficiency. Regional initiatives, such as the SESAR program in Europe, further emphasize the role of technological and operational advancements in upgrading air navigation systems to support both en-route and terminal area movements, contributing to significant environmental and capacity improvements (Malikov, 2023).

Conventional navigation systems, such as the Instrument Landing System (ILS), often struggle to meet modern aviation demands due to limitations in flexibility and efficiency, especially in complex terrain. In contrast, Performance-Based Navigation (PBN) systems, particularly Required Navigation Performance (RNP), offer greater precision and flexibility for safer and more efficient operations. Beyond safety, PBN significantly reduces environmental impacts by optimizing routes to minimize fuel consumption and emissions (ICAO, 2016). These operational and environmental benefits make PBN a transformative innovation in modern air traffic management.

PBN's transformative potential is further underscored by its role in enabling Continuous Climb Operations (CCO) and Continuous Descent Operations (CDO). These techniques minimize fuel consumption, emissions and noise while enhancing air traffic capacity. According to Eurocontrol, full deployment of CCO and CDO across European Civil Aviation Conference (ECAC) airspace could save 340,000 tonnes of fuel, reduce 1 million tonnes of $CO_2$ and generate approximately €150 million in fuel cost savings annually (Ponziani, 2023).

Case studies from major airports around the world illustrate PBN's effectiveness. For example, at San Francisco International Airport, the introduction of RNP to GLS (GBAS Landing System) procedures reduced the approach distance by 20 nautical miles, saving up to 771 kg of fuel per approach and significantly reducing noise exposure for nearby communities. Similarly, at London Stansted Airport, RNP departure routes reduced the number of overflown individuals by 85%, concentrating flight tracks over less populated areas and mitigating noise pollution (Ponziani, 2023). These examples demonstrate how PBN not only addresses operational inefficiencies but also contributes to reducing aviation's environmental footprint.

While global case studies highlight the broad applicability of PBN, research on its implementation in specific contexts has further deepened our understanding of its potential. For instance, Belle et al. (2014) evaluated RNP procedures at Chicago Midway Airport (MDW) and found annual fuel savings of 17,600 gallons. Similarly, Pamplona et al. (2021) utilized simulation-based evaluations to optimize PBN flight paths, demonstrating reduced inefficiencies and fuel consumption. Ding Guo and Dan Huang (2020) analyzed PBN's performance in challenging terrains, noting significant reductions in flight distance, fuel consumption and air traffic controller workloads. Collectively, these studies highlight PBN's adaptability and its ability to improve operational efficiency across diverse environments.

Indonesia's adoption of PBN, which began in 2019, provides further insights into its regional applications. Targeting airports with limited navigation facilities and geographically challenging terrains, PBN implementation in Indonesia has proven effective in enhancing operational efficiency and environmental sustainability. Inderawan et al. (2023) emphasized PBN's role in reducing flight distances, fuel consumption and emissions, aligning with global sustainability goals. Additionally, Sonhaji et al. (2023) demonstrated that RNP Arc-based flight procedures can improve navigation precision in mountainous terrains, achieving fuel savings of up to 1.5% and increasing flight efficiency by 8%. Their study primarily focused on general algorithmic optimizations applied to Instrument Approach Procedures (IAP) at Husein Sastranegara International Airport, Bandung. In contrast, this research evaluates waypoint-specific efficiency using large-scale simulations of 1,000 aircraft per route at Sam Ratulangi International Airport, Manado. By incorporating real operational data from FlightRadar24 into the simulation framework, this study provides a more detailed and robust analysis of PBN's effectiveness in a mountainous environment, addressing operational variability with greater precision.

Previous studies have demonstrated that PBN procedures generally outperform conventional approaches in various contexts, particularly in reducing flight distance, travel time, and fuel consumption (Belle et al., 2014; Pamplona et al., 2021; Ding Guo & Huang, 2020; Ponziani, 2023). However, most of these studies were conducted at airports with relatively flat terrain, such as in the United States and Brazil, and have not assessed PBN's efficiency in mountainous environments like Sam Ratulangi International Airport, Manado. For instance, studies at Chicago Midway Airport (MDW) (Belle et al., 2014) and London Stansted Airport (Ponziani, 2023) have demonstrated significant fuel savings and noise reduction, yet these locations lack complex terrain constraints. Meanwhile, Ding Guo and Huang (2020) highlighted the benefits of PBN in challenging environments, but their analysis did not focus on waypoint-specific evaluations crucial for understanding PBN's precise efficiency. Additionally, these studies did not incorporate simulations utilizing real FlightRadar24 data to capture operational variability, limiting their applicability to real-world scenarios.

This study introduces a novel approach to evaluating the fuel efficiency of PBN and ILS procedures by simulating 30 aircraft per route using real operational speed data obtained from FlightRadar24. Unlike previous research that often relied on hypothetical or small-scale datasets, this study employs actual flight data to ensure a realistic and robust representation of air traffic performance.

Additionally, this is the first study in Indonesia to compare PBN and ILS efficiency at a geographically complex airport like Sam Ratulangi International Airport, which is surrounded by mountainous terrain. Previous studies have largely focused on flat-terrain airports, leaving a significant gap in understanding how PBN performs in airports with complex geographical constraints.

By combining simulation-based analysis with waypoint-specific evaluations, this research bridges an existing gap in the literature and offers practical insights for optimizing approach procedures at airports facing similar challenges. The findings contribute to fuel efficiency improvements, reduced operational costs and sustainable aviation practices, reinforcing the strategic importance of PBN implementation in complex airspace environments.

This research aims to fill these gaps by evaluating the efficiency of RNP-based and ILS approach procedures at Sam Ratulangi International Airport using the BlueSky simulator. The analysis focuses on fuel consumption, flight time and distance, with findings expected to provide practical recommendations for enhancing navigation procedures in mountainous airports like Manado. To ensure statistical reliability and operational realism, the study simulated 30 aircraft using real speed data from FlightRadar24, reflecting real-world operational variability while balancing computational feasibility with the need for robust and representative findings.

## 2. Methodology

This study adopts a quantitative approach to evaluate the fuel efficiency of Performance-Based Navigation (PBN) and Instrument Landing System (ILS) procedures. The analysis focuses on approach procedures from the LUANG waypoint to Runway 36 at Sam Ratulangi International Airport, Manado. The research methodology is structured into four main stages: data collection, processing, simulation and analysis. The overall process is illustrated in Process Flow of Methodology (Figure 2-1), which outlines the sequential steps undertaken, from collecting real-world data to analyzing the simulation results.

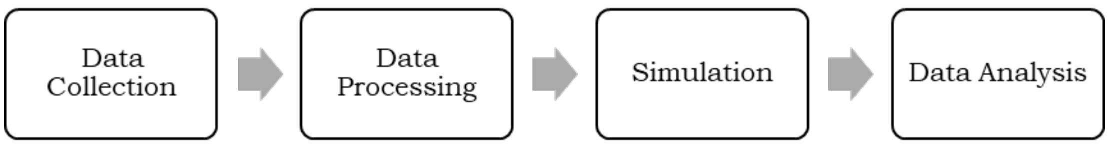


**Figure 2-1:** Process Flow of Methodology.

### 2.1. Related Works

Numerous studies have examined the benefits of Performance-Based Navigation (PBN) compared to conventional procedures in aviation. Belle and Sherry (2014) analyzed the implementation of Required Navigation Performance (RNP) at Chicago Midway Airport, demonstrating an annual fuel savings of 17,600 gallons through optimized approach paths. Similarly, Guo and Huang (2021) highlighted the advantages of PBN in reducing flight distance and fuel consumption at airports with complex terrain while also enhancing airspace capacity in flat-terrain regions. Pamplona et al. (2021) explored the use of simulation techniques to evaluate PBN performance, emphasizing the environmental benefits of reduced carbon emissions.

In Indonesia, Inderawan et al. (2023) underscored the role of PBN in supporting sustainable aviation by improving flight efficiency in enroute segments. These findings align with global efforts to modernize air navigation systems and address challenges in aviation sustainability. However, comparative studies specifically analyzing the efficiency of PBN versus ILS in approach operations remain limited, particularly in airports with complex geographical characteristics such as Sam Ratulangi International Airport in Manado.

While prior research has demonstrated the benefits of PBN in various environments, most studies have focused on airports with relatively flat terrain, such as those in the United States and Brazil. These studies primarily assess PBN's advantages in terms of fuel efficiency and flight time savings but do not evaluate its performance in mountainous regions where conventional procedures may be significantly affected by terrain constraints. Moreover, many of these studies use deterministic modeling with a limited number of scenarios, which may not fully capture real-world operational variability.

To address these gaps, this study incorporates simulations of 30 aircraft per route using real-time FlightRadar24 data to ensure realistic operational representation. By focusing on this detailed evaluation, the research provides valuable insights into the comparative efficiency of PBN and ILS in a challenging geographical setting, emphasizing the operational benefits of PBN in terrain-constrained environments.

### 2.2. Problem Definition

The aviation industry faces increasing pressure to balance the growth of air transportation with sustainability goals, particularly in reducing fuel consumption and carbon emissions. Conventional navigation systems like ILS, while reliable, often struggle with inefficiencies in approach procedures, especially at airports surrounded by challenging terrain. These inefficiencies lead to longer flight distances, higher fuel consumption and increased environmental impact.

Sam Ratulangi International Airport, located in Manado, Indonesia, presents a unique operational challenge due to its mountainous surroundings. While PBN has shown promise in optimizing flight operations, its benefits have not been thoroughly quantified in this context. The key problem addressed in this study is the need for a detailed comparative analysis of PBN (RNP) and ILS approach procedures at this airport, focusing on metrics such as fuel consumption, flight distance and time. By addressing this gap, the study aims to provide actionable insights to improve operational efficiency and support the broader adoption of PBN systems in Indonesia and beyond.

### 2.3. Method

#### 2.3.1. Data Collection

The simulation incorporated 30 aircraft using real speed data obtained from FlightRadar24, a reliable source for real-time aircraft tracking and performance metrics. The sample size of 30 was determined using the formula proposed by Viechtbauer et al. (2015), which is widely used in statistical power analysis to ensure robust and reliable results in comparative studies. This formula is particularly suitable for this research because it accounts for variability in real-world data while maintaining a balance between statistical power and computational feasibility.

Given that this study compares PBN and ILS procedures using simulated flight data, it is essential to ensure that the selected sample size adequately represents operational conditions while minimizing the risk of Type I and Type II errors. By applying the Viechtbauer formula, the sample size was calculated based on an expected effect size, confidence level and acceptable margin of error, ensuring that the results are statistically meaningful.

Furthermore, the decision to use 30 aircraft samples aligns with best practices in aviation research, where real-world flight variability must be captured to make meaningful comparisons. The use of real FlightRadar24 speed data in the simulation adds further credibility, as it reflects actual aircraft performance in operational conditions. This approach ensures that the conclusions drawn from the study are both valid and applicable to real-world air traffic management scenarios. The sample size was calculated using the formula:

$$n = \frac{\ln(1-C)}{\ln(1-p)} \qquad (2\text{-}1)$$

Where:
- $n$ : Required sample size
- C : Confidence Level (95%)
- p : The estimated probability of occurrence (0.1)

$$n = \frac{\ln(1-0.95)}{\ln(1-0.1)} = \frac{ln(0.05)}{ln(0.9)} \approx \frac{-2.9957}{-0.1054} \approx 28.4$$

This calculation resulted in a sample size of approximately 29. To account for practical considerations and potential variations, the sample size was rounded up to 30 aircraft, ensuring statistical reliability while reflecting real-world operational variability. The data collected included speed variations for specific waypoints, capturing the nuances of actual flight operations under varied conditions. This approach balances computational feasibility with the robustness required to draw meaningful insights from the simulation.

2.3.1.1 Real-Time Data Source

Aircraft speeds were collected via FlightRadar24, as illustrated in the Real-Time Aircraft Speed Data from FlightRadar24 (Figure 2-2). These data were analyzed to provide speed inputs for 30 simulated aircraft operating in the approach segment between the LUANG waypoint and Runway 36. To isolate the impact of navigation procedures on operational efficiency, real speeds from PBN flights were applied uniformly across both PBN and ILS simulations. This ensures that observed differences are attributable to the procedural characteristics, not discrepancies in input speed (Table 2-1).

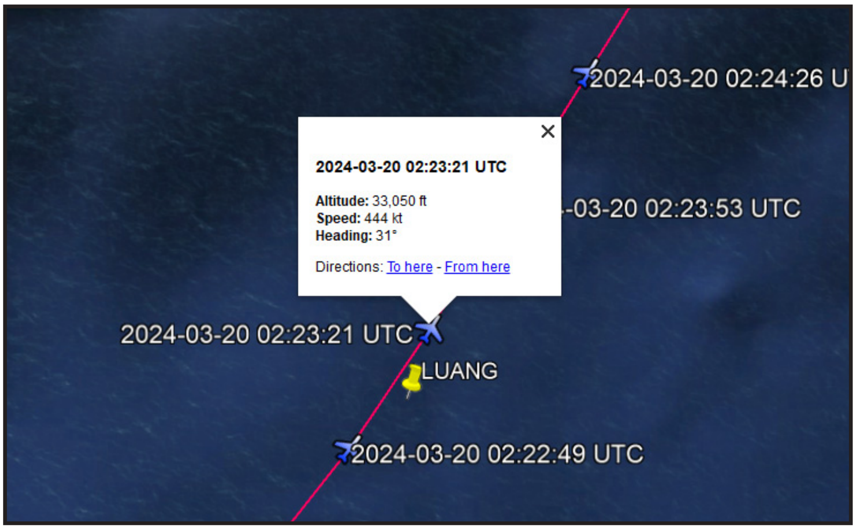


**Figure 2-2:** Real-Time Aircraft Speed Data from FlightRadar24

**Table 2-1:** Aircraft Speed Data for Each Waypoint (Knots)

| DATA | LUANG | LOVPO | NOMOG | PONAR | MM801 | MM802 |
|---|---|---|---|---|---|---|
| Sample #01 | 454 | 389 | 323 | 257 | 180 | 157 |
| Sample #02 | 454 | 358 | 311 | 242 | 215 | 157 |
| Sample #03 | 481 | 336 | 254 | 202 | 159 | 150 |
| Sample #04 | 453 | 365 | 225 | 194 | 152 | 160 |
| ..... | ..... | ..... | ..... | ..... | ..... | ..... |
| ..... | ..... | ..... | ..... | ..... | ..... | ..... |
| ..... | ..... | ..... | ..... | ..... | ..... | ..... |
| ..... | ..... | ..... | ..... | ..... | ..... | ..... |
| Sample #30 | 455 | 389 | 333 | 253 | 177 | 160 |

2.3.1.2. Waypoint and Scenario Design

a. Waypoints and Coordinates: Waypoint coordinates were obtained from the Indonesian Aeronautical Information Publication (AIP) Vol II, which serves as the official source of aeronautical navigation data in Indonesia. The AIP provides precise geographical coordinates, altitude restrictions and procedural details for standard instrument approaches, ensuring accuracy in waypoint placement within the simulation. These waypoints define the trajectory of both PBN and ILS approach procedures at Sam Ratulangi International Airport, enabling a realistic comparison of their operational efficiency.
b. Scenario Templates: Two BlueSky simulation scenarios were generated using a Python script: one representing the RNP procedure and the other representing the ILS procedure. Each scenario included 30 aircraft, with individual speeds sampled from real FlightRadar24 data to reflect actual operational conditions. The waypoints leading to Runway 36 were defined based on official aeronautical sources, ensuring accuracy in trajectory replication. By maintaining consistent environmental parameters across both procedures, this approach enables a controlled comparison of fuel efficiency, flight time and distance between RNP and ILS approaches.
c. Approach Procedures: Two procedures were modeled:
   1. PBN Procedure: The Performance-Based Navigation (PBN) procedure, represented by Required Navigation Performance (RNP), utilizes satellite-based navigation and onboard performance monitoring to provide highly precise lateral and vertical guidance. RNP enables optimized flight paths, reducing fuel consumption, flight time and environmental impact by avoiding unnecessary route deviations and enabling more direct trajectories. This approach is particularly advantageous in challenging terrains, such as those surrounding Sam Ratulangi International Airport, where conventional navigation systems often face limitations. The flexibility of RNP procedures allows aircraft to navigate through complex airspaces with improved efficiency and safety, eliminating the reliance on ground-based navigation aids while maintaining high levels of operational precision (ICAO, 2016).

   2. ILS Procedure: The Instrument Landing System (ILS) procedure represents a conventional ground-based navigation approach. ILS provides lateral guidance through a localizer and vertical guidance through a glide slope, enabling accurate approaches in low-visibility conditions. However, ILS systems are constrained by the need for extensive ground infrastructure and fixed installation sites, limiting flexibility and adaptability to terrain challenges. In mountainous areas like Manado, ILS often requires longer and less efficient routing to align aircraft with the runway, leading to increased fuel consumption and operational costs. Despite its reliability, ILS lacks the adaptability of PBN, making it less effective in environments with significant geographical constraints.

2.3.1.3. Simulation Platform

The BlueSky ATM Simulator is an open-source platform developed by TU Delft, designed to model Air Traffic Management (ATM) and air traffic flows. It provides researchers with a powerful tool for visualizing, analyzing and simulating flight scenarios without licensing restrictions, making it freely accessible (Ongkowijoyo et al., 2021). Due to its flexibility and reliability, BlueSky has been widely adopted in academic research. Schornagel (2022) demonstrated its application in improving climb and descent profiles using ATC performance models, emphasizing its ability to simulate real-world scenarios with high accuracy.

For this study, BlueSky was used to simulate approach procedures at Sam Ratulangi International Airport. The simulation modeled 30 aircraft, each operating from the LUANG waypoint to Runway 36, following either the PBN (RNP) or ILS procedure. To ensure realistic and operationally valid conditions, the aircraft speeds were obtained from real-time FlightRadar24 data, where each aircraft was assigned its actual recorded speed during the approach phase. This approach ensures that the simulated results accurately reflect real-world variations in aircraft performance, improving the validity of flight distance, time and fuel consumption measurements. By leveraging BlueSky's robust simulation capabilities, this study provides a direct, controlled comparison of PBN and ILS procedures, while ensuring consistency in operational parameters.

2.3.2. Data Processing

Once the aircraft speed data were obtained from FlightRadar24, they were integrated into scenario templates for each approach procedure. Two distinct scenario templates were created: one for the RNP procedure (Figure 2-3) and one for the ILS procedure (Figure 2-4). Each template contained waypoints, routing details and procedural elements specific to the respective approach to ensure consistency in the comparison.

To enhance the realism of the simulation, Python was employed to generate 30 aircraft instances for each approach procedure. The script systematically assigned unique aircraft identifiers and incorporated real speed values for each waypoint, extracted from FlightRadar24. This method ensured that each simulated aircraft adhered to realistic operational speeds while maintaining procedural consistency.

The finalized scenarios, consisting of 30 aircraft and their corresponding speed data, were saved in the *.scn format, ensuring full compatibility with the BlueSky ATM Simulator. This approach enabled seamless execution of the simulation while preserving the integrity of real-world flight dynamics.

```
00:00:00.00>CRELOG LUANGRNPVILS 1.0
00:00:00.00>LUANGRNPVILS ADD traf.id traf.distflown
00:00:00.00>LUANGRNPVILS ON

#LUANGRNP WARR-WAMM A5
00:00:00.00>CRE LUANG1 B738 -0.274735 123.776518 020 FL270 0
00:00:00.00>SPD LUANG1 400
00:00:00.00>LUANG1 DEST WAMM RWY36
00:00:00.00>LUANG1 VNAV ON
00:00:00.00>LUANG1 LNAV ON
00:00:00.00>TRAILS ON
00:00:00.00>LUANG1 ADDWPT 0.072222 123.848611 FL270 456 #LUANG
00:00:00.00>LUANG1 ADDWPT 0.92638889 124.37250000 FL240 358 #LOVPO
00:00:00.00>LUANG1 ADDWPT 1.22583333 124.55611111 FL100 278 #NOMOG
00:00:00.00>LUANG1 ADDWPT 1.26616667 124.74880556 8000 211 #PONAR
00:00:00.00>LUANG1 ADDWPT 1.26397222 124.91700000 5200 183 #MM801
00:00:00.00>LUANG1 ADDWPT 1.35247222 124.91980556 4200 166 #MM802
00:00:00.00>LUANG1 ADDWPT 1.41100000 124.92175000 2990 154 #MM803
00:00:00.00>LUANG1 ADDWPT WAMM 0 0 #LANDING
```

**Figure 2-3:** RNP Scenario

```
00:00:00.00>CRELOG LUANGRNPVILS 1.0
00:00:00.00>LUANGRNPVILS ADD traf.id traf.distflown
00:00:00.00>LUANGRNPVILS ON

#LUANGILS WARR-WAMM 11
00:04:35.00>CRE LUANG2 B738 -0.274735 123.776518 020 FL270 0
00:04:35.00>SPD LUANG2 400
00:04:35.00>LUANG2 DEST WAMM RWY36
00:04:35.00>LUANG2 VNAV ON
00:04:35.00>LUANG2 LNAV ON
00:04:35.00>TRAILS ON
00:04:35.00>LUANG2 ADDWPT 0.072222 123.848611 FL270 456 #LUANG
00:04:35.00>LUANG2 ADDWPT FLYOVER
00:04:35.00>LUANG2 ADDWPT MWB FL100 280 #MWBVOR
00:04:35.00>LUANG2 ADDWPT MNO 4500 274 #MNOVOR
00:04:35.00>LUANG2 ADDWPT 1.608509 124.914272 4500 254
00:04:35.00>LUANG2 ADDWPT 1.60635556 124.93108889 4500 254
00:04:35.00>LUANG2 ADDWPT 1.45692778 124.88149444 3000 254 #D6.5MNO
00:04:35.00>LUANG2 ADDWPT 1.44697222 124.92291667 2200 220 #FAF
```

**Figure 2-4:** ILS Scenario

### 2.3.3. Simulation

#### 2.3.3.1 Execution in BlueSky

The BlueSky platform was utilized to execute two distinct scenarios: one for the RNP procedure (Figure 2-5) and one for the ILS procedure (Figure 2-6). Throughout the simulation, the platform recorded aircraft movement at one-second intervals, tracking the total distance flown from the LUANG waypoint to the Runway 36 threshold. All recorded data were automatically stored in log files, which were subsequently processed and converted for further analysis to evaluate the comparative performance of each approach procedure.

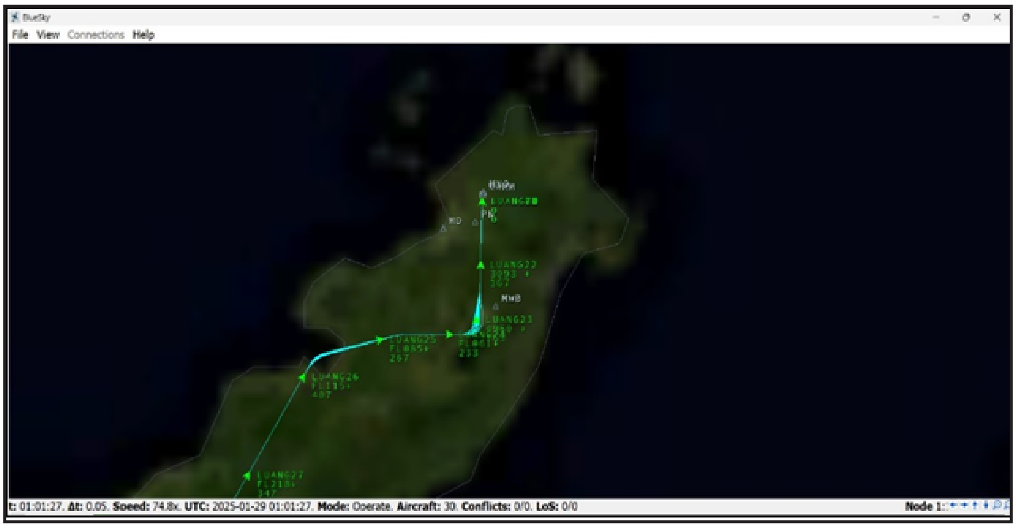


**Figure 2-5:** Simulation of RNP Approach Procedures


**Figure 2-6:** Simulation of ILS Approach Procedures

#### 1.1.1.2 Log File Conversion

Following the completion of the simulation, the raw log files generated by the BlueSky ATM Simulator were extracted and processed for further analysis. These log files contained detailed flight data, including recorded timestamps, distances traveled and elapsed time.

To facilitate statistical analysis, the log files were converted into Microsoft Excel format, ensuring compatibility with widely used analytical tools. The recorded distance values, initially measured in meters, were converted into kilometers, while time values, originally logged in seconds, were standardized into minutes. These conversions were necessary to align the data with aviation industry conventions and enhance interpretability when comparing flight performance metrics between the PBN and ILS procedures.

Furthermore, any missing or anomalous data points were reviewed and filtered to maintain the accuracy and consistency of the dataset. The finalized Excel files were structured to enable efficient computation of key performance indicators, including total flight distance and flight duration.

The standardized dataset served as the foundation for comparative analysis, allowing for a precise evaluation of the efficiency differences between PBN and ILS approaches under simulated conditions. Table 2-2 presents the standardized flight performance data for the RNP approach, illustrating the converted distance and time values. The same procedure was applied to the ILS scenario to ensure consistency in data processing and comparability across both approach types.

**Table 2-2:** Conversion of Log File Data for Distance and Time Standardization

| Aircraft Id | Distance (m) | Distance (km) | Time (sec) | Time (min) |
|---|---|---|---|---|
| LUANG1 | 257.521 | 257,5 | 1.309 | 21,8 |
| LUANG2 | 258.047 | 258,0 | 1.323 | 22,1 |
| LUANG3 | 258.638 | 258,6 | 1.408 | 23,5 |
| LUANG4 | 258.837 | 258,8 | 1.425 | 23,8 |
| LUANG5 | 258.676 | 258,7 | 1.325 | 22,1 |
| ..... | ..... | ..... | ..... | ..... |
| ..... | ..... | ..... | ..... | ..... |
| ..... | ..... | ..... | ..... | ..... |
| LUANG30 | 257.598 | 257,6 | 1.297 | 21,6 |

1.1.1.3 Fuel Consumption Calculation

Fuel consumption was calculated using the formula:

$$FC = Dist \times FBR \times nS \quad (2\text{-}2)$$

Where:

• FC : Fuel Consumption (kg)
• Dist : Distance flown (km)
• FBR : Fuel Burn Rate (kg/km/seat). In this study, the value used is 0.02093 kg/km/seat, sourced from Kühn (2023).
• nS : Number of seats, assumed as 150 for narrow-body aircraft configurations typical for the A320. This seating capacity is based on the dual-class layout described in the A320 specifications provided by Aircraft Commerce (2006).

This formula allows for the estimation of total fuel consumption per flight based on the distance traveled and the specified operational parameters.

To illustrate the application of Eq. (2-2), an example calculation for the LUANG1 aircraft operating under the RNP procedure is provided. The total fuel consumption (FC) is estimated based on the distance flown, fuel burn rate per kilometer per seat (FBR), and the number of seats (nS). For LUANG1, the following parameters were used:

• Dist : 257.5 km

• FBR : 0.02093 kg/km/seat

• nS : 150

Using Eq. (2-2):

$$FC = 257.5 \times 0.02093 \times 150 = 808.48 \approx 808.5\ kg$$

This result represents the total fuel consumption for LUANG1 during the simulated RNP approach procedure. Similar calculations were performed for all aircraft in the dataset, enabling a comprehensive comparison of fuel consumption across different procedures.

2.3.4. Data Analysis

The final stage of this study involved analyzing the simulation results to compare the metrics of flight distance, flight time, and fuel consumption between PBN and ILS procedures. For each procedure, 30 simulated flights were analyzed, focusing on aggregated metrics to ensure a thorough and representative comparison (Table 3-1). Fuel consumption was calculated using the formula outlined in Eq. (2-2), while the recorded distance and time values were extracted from the simulation logs for each flight.

The efficiency of each approach was assessed by calculating both the absolute values and the average percentage differences across all 30 flights for each metric. This approach ensures a robust and comprehensive comparison, highlighting the operational benefits of PBN over ILS procedures. By incorporating multiple flights and accounting for potential variability in real-world conditions, the analysis provides meaningful insights into the relative efficiency of these navigation procedures.

## 3. Result and Analysis

### 3.1. Flight Distance and Time

The results reveal notable differences in flight distance and time between the ILS and RNP procedures from the LUANG waypoint to Runway 36 (Table 3-1). The RNP procedure consistently demonstrated better performance compared to the ILS procedure in both metrics. Specifically, the average flight distance for the RNP procedure was 258.5 km, which is 14% shorter than the 299.2 km recorded for the ILS procedure.

In terms of flight time, the RNP approach required an average of 22.6 minutes, compared to 26.7 minutes for the ILS procedure. This translates to a time reduction of approximately 15%, underscoring the efficiency of the RNP procedure in streamlining the approach path.

These reductions in flight distance and time highlight the advantages of the RNP procedure in providing more direct routing, reducing deviations, and optimizing the overall approach trajectory. Such improvements not only enhance operational efficiency but also contribute to fuel savings and simplified air traffic management, reinforcing the benefits of adopting Performance-Based Navigation systems in challenging geographical environments.

### 3.2. Fuel Consumption

The analysis of fuel consumption demonstrates a substantial improvement with the RNP procedure (Table 3-1). The average fuel consumption for RNP was 811.5 kg, which is approximately 14% lower than the 939.3 kg recorded for the ILS procedure.

These fuel savings are directly attributed to the shorter flight distance and reduced flight time achieved through the RNP approach. By optimizing the descent and landing trajectory, the RNP procedure significantly minimizes operational fuel requirements, thereby reducing costs and enhancing environmental sustainability. This efficiency is particularly critical in the context of rising fuel prices in the aviation industry, positioning RNP as a key strategy for achieving both cost-effectiveness and sustainable aviation practices.

**Table 3-1:** Comparison of Performance Metrics for ILS and RNP Procedures at LUANG Waypoint

| Parameters | ILS | RNP | Saving | Differences |
|---|---|---|---|---|
| Distance (Km) | 299,2 | 258,5 | 40,7 | 14% |
| Time (Minutes) | 26,7 | 22,6 | 4,1 | 15% |
| Fuel Consumption (Kg) | 939,3 | 811,5 | 127,8 | 14% |

The values presented in Table 3-1 represent the average metrics calculated across all 30 simulated flights for each procedure (RNP and ILS). These averages provide a comprehensive summary of the performance differences between the two procedures in terms of flight distance, flight time, and fuel consumption. The average distance, time, and fuel consumption were computed by summing the respective values for all 30 flights and dividing by the total number of flights. This approach ensures that the comparisons are statistically robust and account for any variability in individual flight performances within the simulation.

### 3.3. Analysis

3.3.1 Flight Track Analysis

The flight tracks generated from the simulations reveal distinct differences in the routing patterns of RNP and ILS procedures, highlighting the operational advantages of RNP (Figure 2-5 and Figure 2-6). The RNP procedure exhibits a streamlined and direct flight path, with minimal deviations and sharp turns, resulting in a shorter overall route. In contrast, the ILS procedure demonstrates a more circuitous and variable path, characterized by extended routing and multiple alignment turns to establish a precise approach to the runway.

The increased variability in the ILS procedure can be attributed to its reliance on ground-based navigation aids, requiring aircraft to align with the localizer and glide slope over a longer distance. This results in additional maneuvers and elongated flight paths, particularly in areas with challenging terrain or complex airspace configurations. Furthermore, at higher speeds, aircraft following the ILS procedure require larger turning radii, further contributing to route inefficiency.

The RNP procedure leverages satellite-based navigation, enabling precise lateral and vertical guidance throughout the approach. This precision allows for shorter and more efficient routing, as aircraft can maintain optimized trajectories without reliance on fixed ground-based infrastructure. The resulting reduction in flight distance and deviations underscores the operational benefits of RNP, particularly in mountainous regions such as Sam Ratulangi International Airport.

These routing differences have significant implications for fuel consumption and flight time. The streamlined RNP track minimizes energy expenditure, reducing both operational costs and environmental impact. In contrast, the extended routing of the ILS track increases fuel burn and flight time, further emphasizing the efficiency of RNP in terrain-constrained environments. This analysis reinforces the necessity of adopting Performance-Based Navigation systems to achieve sustainable and cost-effective operations in modern air traffic management.

### 3.3.2 Fuel Efficiency and Operational Insights

The findings of this study provide a deeper understanding of the comparative efficiency of Performance-Based Navigation (PBN) and Instrument Landing System (ILS) procedures, particularly in terms of fuel consumption, flight time, and adaptability to challenging terrains. The results underscore the significant advantages of Required Navigation Performance (RNP) approaches, especially when operating at airports with complex geographic features like Sam Ratulangi International Airport.

One of the most compelling findings is the reduction in fuel consumption achieved through the RNP procedure. This improvement stems from three critical factors:

1. Optimized Routing

   As demonstrated in the flight track analysis, RNP procedures enable shorter and more direct paths by minimizing deviations and eliminating excessive alignment maneuvers. The efficiency of RNP in reducing flight distance directly translates to reduced energy expenditure, as supported by the quantitative data presented in this study.

2. Enhanced Altitude and Speed Management

   PBN systems, particularly RNP, allow for smoother descents and optimized speed profiles during the approach phase. This operational precision reduces unnecessary fuel burn associated with abrupt level-offs or corrections. As highlighted by Honeywell Aerospace (2019), such precise altitude and speed management plays a pivotal role in improving fuel efficiency, particularly in high-traffic or terrain-constrained environments.

3. Adaptability to Terrain Constraints

   The mountainous terrain surrounding Sam Ratulangi International Airport poses significant challenges for conventional navigation systems like ILS, often resulting in extended routing or holding patterns. RNP, by leveraging satellite-based navigation, provides the flexibility to navigate through complex terrain efficiently, avoiding the inefficiencies inherent to ILS approaches.

### 3.3.3 Implications and Benefits of the Analysis

The results of this study highlight several important implications for aviation operations, particularly concerning the adoption of Performance-Based Navigation (PBN) systems.

The analysis provides actionable insights that could inform decision-making for both airport management and airline operators, emphasizing the broader benefits of transitioning to modern navigation technologies such as Required Navigation Performance (RNP).

1. Operational Cost Savings

   One of the most tangible benefits demonstrated by the analysis is the reduction in fuel consumption associated with RNP procedures. With aviation fuel accounting for a significant portion of airline operating expenses, the 14% reduction in fuel consumption compared to ILS procedures translates directly into cost savings. These savings not only improve the financial sustainability of airlines but also enhance their competitiveness, especially in regions where profit margins are thin.

2. Environmental Sustainability

   The reduced fuel consumption observed with RNP approaches also contributes to lowering carbon emissions. Given the aviation industry's global commitment to achieving net-zero emissions by 2050 under frameworks like CORSIA, adopting RNP could serve as a practical step toward meeting these targets. The findings demonstrate that modernizing approach procedures with PBN systems can significantly reduce aviation's environmental footprint without compromising operational safety or efficiency.

3. Enhanced Airspace Efficiency

   The direct and optimized routing enabled by RNP minimizes flight path variability and simplifies air traffic management. This predictability reduces the workload for both pilots and air traffic controllers, fostering a safer and more efficient operating environment. Additionally, the ability of RNP to handle complex terrains and high-traffic conditions could enhance airspace capacity, enabling airports like Sam Ratulangi to accommodate future growth in air traffic demand.

4. Scalability and Adaptability

   The findings also underscore the scalability of RNP procedures for broader applications. While this study focuses on Sam Ratulangi International Airport, the benefits of RNP can be replicated at other airports with challenging geographic conditions or limited infrastructure for conventional navigation systems. The flexibility of PBN makes it a valuable tool for addressing diverse operational challenges across the aviation industry.

## 4. Conclusions

The findings of this study clearly demonstrate that Performance-Based Navigation (PBN) procedures, represented by Required Navigation Performance (RNP), offer significant advantages over conventional Instrument Landing System (ILS) procedures in approach operations at Sam Ratulangi International Airport, Manado. The analysis revealed that RNP procedures consistently surpassed ILS in operational metrics, achieving an average fuel consumption reduction of 127.8 kg per flight, equivalent to an improvement of approximately 14%. Furthermore, RNP procedures resulted in shorter flight distances and reduced flight times, underscoring their superior efficiency and effectiveness in optimizing approach operations.

The total potential fuel savings per year at Sam Ratulangi International Airport could reach 459,391 kg. This figure was calculated based on the weekly flight frequencies at the LUANG waypoint, which total 69 flights per week. Assuming 52 weeks per year, this results in a total of 3,588 flights annually. With an average fuel saving of 127.8 kg per flight, the total annual savings were derived to 459,391.2kg.

Based on the Pertamina aviation fuel price for MDC (Sam Ratulangi International Airport) at IDR 14,925.33 per liter and considering the density of Jet A-1 fuel at approximately 0.8 kg per liter, the equivalent fuel price per kilogram is IDR 18,656.66 (Pertamina, 2024). Using this price, the total estimated cost savings would reach approximately IDR 8.57 billion (USD ~550,000), confirming the substantial financial impact of optimizing fuel consumption.

To put this into perspective, IDR 8.57 billion is equivalent to the cost of operating numerous short-haul flights per year. For a narrow-body aircraft like the Boeing 737-800, which consumes approximately 2,500 kg of fuel per hour, these savings could fully cover the fuel costs for over 183 one-hour domestic flights. In other words, by simply switching to PBN procedures at Sam Ratulangi Airport, an airline could potentially operate additional routes with zero fuel cost, dramatically improving overall profitability.

These savings become even more critical as fuel costs make up 20-30% of airline operating expenses, directly influencing ticket pricing, operational efficiency, and long-term financial sustainability. In a highly competitive industry where margins are thin and profitability depends on cost optimization, even single-digit percentage reductions in fuel burn can determine whether a route remains profitable or not. For budget airlines, which rely on volume and cost efficiency, this kind of savings could be the difference between expansion or route cancellation.

Beyond the economic benefits, this efficiency also translates into an annual $CO_2$ reduction of up to 1.45 million kg, a substantial contribution to global aviation decarbonization efforts. This figure is derived from the total fuel savings of 459,391 kg, with each kilogram of Jet A-1 fuel producing approximately 3.16 kg of $CO_2$ emissions. To put this into context, 1.45 million kg of $CO_2$ is roughly equivalent to the carbon emissions produced by over 310 passenger vehicles in a year. These numbers underscore the urgent need for airlines to optimize navigation procedures as part of a broader strategy to reduce the industry's environmental footprint (EPA, 2024).

The aviation sector is currently under immense pressure to reduce carbon emissions, with global regulations tightening under initiatives like the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) and net-zero emission targets set for 2050 by the International Air Transport Association (IATA). Airlines that fail to implement fuel-efficient procedures will face increasing financial penalties, carbon taxes, and potential operational restrictions as governments and international bodies intensify sustainability mandates.

Looking toward the future, fuel efficiency and emissions reduction are no longer optional improvements—they are absolute necessities for the survival of the aviation industry. If $CO_2$ emissions continue unchecked, climate change will intensify extreme weather patterns, disrupt global supply chains, and create significant operational risks for airlines. Sustainable aviation practices like Performance-Based Navigation (PBN) provide a viable solution to mitigate these risks by cutting unnecessary fuel burn and reducing aviation's environmental impact.

These findings reinforce the importance of modernizing air traffic procedures, particularly in airports where conventional ILS approaches impose unnecessary fuel penalties due to extended routing constraints. The aviation industry must act now—not just for cost savings, but for the long-term sustainability of air travel and the protection of future generations.

This study also addresses a key research gap by evaluating PBN efficiency in a geographically complex airport, contrasting it with prior studies largely conducted in flat-terrain environments. Unlike previous research, which primarily analyzed general algorithms or deterministic models, this study utilizes waypoint-specific evaluations and large-scale simulations incorporating real operational data from FlightRadar24. This approach provides a detailed and realistic analysis of operational variability in a mountainous environment, offering insights that can guide navigation optimization at other airports facing similar topographical constraints.

While the scope of this study is limited to a single waypoint and approach configuration, its findings highlight the broader potential of PBN systems in enhancing air traffic operations. Future research could expand this analysis by investigating multiple waypoints, varying traffic conditions and the economic feasibility of PBN implementation across different airport types. Integrating real-world operational data from airlines and air traffic management systems could further validate the robustness of PBN's benefits.

The results reaffirm the critical importance of modernizing air traffic procedures. As fuel costs remain a major component of airline expenses, PBN provides a pathway to reducing operational costs while promoting environmental sustainability. Stakeholders—including airlines, air navigation service provider, regulators and researchers—must collaborate to accelerate the adoption of PBN systems, ensuring that the aviation industry meets its dual challenges of rising operational expenses and global decarbonization goals. For airports like Sam Ratulangi International, PBN is not merely an operational improvement—it is an essential tool for securing the future of sustainable air travel.

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