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Stochastic Simulation of Landing Procedure Efficiency: A Case Study at Sam Ratulangi Airport

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ABSTRACT

This study compares the operational efficiency of instrument landing system (ILS) and required navigation performance (RNP) approach procedures at Sam Ratulangi International Airport, Manado, Indonesia. Stochastic simulations were conducted using the BlueSky ATM Simulator with 1,000 flights per waypoint, and speeds were collected from FlightRadar24 observations. The results indicated that RNP procedures reduce flight distance and time at GOTSA, as well as at SOSOK and LUANG for Runway 36, resulting in considerable reductions in travel distance and measurable time savings. Fuel efficiency improvements were also observed under the most favorable RNP conditions, while ILS remained more efficient on selected routes for Runway 18. Overall, RNP provides more predictable and generally more efficient arrival operations, but route-specific terrain constraints and procedure design considerations must be carefully evaluated prior to implementation.

Keywords: Landing procedures; Stochastic simulation; Air traffic efficiency; Fuel optimization.

INTRODUCTION

The aviation industry faces a critical challenge: managing rapid growth in air transport services while minimizing environmental impact. Aircraft emissions increased by 6.8 times between 1960 and 2018, and pre-pandemic projections indicated a threefold increase between 2020 and 2050 (Gossling and Humpe 2020; Lee et al. 2020). Although COVID-19 temporarily slowed traffic growth, recovery to pre-pandemic levels has renewed concerns about emissions and sustainability (Gudmundsson *et al.* 2021). Modernizing air traffic management and adopting efficient navigation technologies are essential steps toward achieving global decarbonization targets.

Performance-based navigation

Conventional ground-based navigation systems such as very-high frequency omnidirectional range (VOR), non-directional beacon (NDB), and instrument landing system (ILS) use onboard aircraft receivers to interpret signals from ground facilities, but route design remains constrained by the location and coverage of those facilities (FAA, 2025). To address these issues, the International Civil Aviation Organization (ICAO) introduced performance-based navigation (PBN) in the Global Air Navigation Plan (Doc 9,750), enabling route design based on defined navigation performance requirements rather than solely on ground-based aid locations (ICAO 2016).

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Environmental and operational benefits

Beyond operational improvements, PBN contributes significantly to environmental sustainability (Meric 2015; Agustini *et al.* 2024). Studies have shown that PBN implementation can reduce CO_2 emissions by 1,164–3,678 tons annually at airports such as Ahmedabad, India, and decrease fuel consumption by 65–96 kg per flight in Prague, Czech Republic. These benefits align with global efforts to reduce aviation's carbon footprint.

Performance-based navigation implementation in Indonesia

Indonesia began implementing PBN in 2019 under the ICAO Air Navigation Block Upgrade roadmap, collaborating with AirNav Indonesia and European Union Aviation Safety Agency (EASA). Initial deployment targeted airports with limited navigation facilities, and expansion continues to improve safety and efficiency nationwide. Given Indonesia's complex geography, mountainous terrain and remote islands, PBN offers a strategic solution for optimizing flight operations (Airbus 2021, Guo and Huang 2021).

Research gap and objectives

While global studies highlight PBN's advantages, comparative analyses of conventional ILS and PBN-based approaches in Indonesia remain limited. No prior study has quantified the efficiency difference between ILS and required navigation performance (RNP) approaches in Indonesian airports. This study addresses that gap by evaluating approach efficiency at Sam Ratulangi International Airport, Manado, an airport surrounded by challenging terrain, including Mount Klabat (6,549 ft), Mount Soputan (4,600 ft), and Mount Manado Tua (2,628 ft) (Hutomo and Ahyudanari 2018). The research compared ILS and RNP approaches in terms of flight distance, time, and fuel consumption using stochastic simulation. The hypothesis was that PBN-based procedures outperform conventional methods across these metrics.

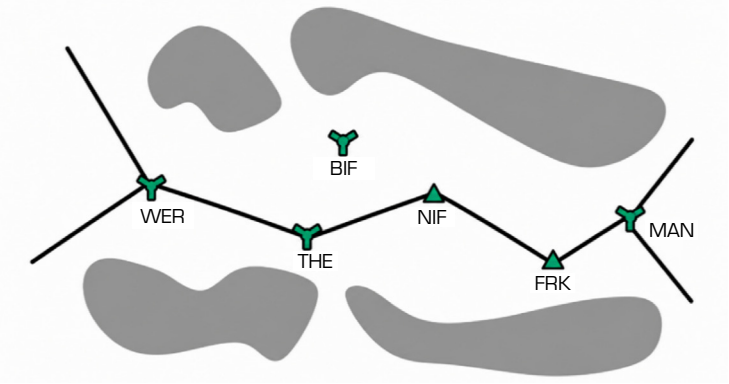
The problem addressed in this study was the absence of waypoint-level quantitative evidence showing when RNP procedures provide measurable efficiency benefits over conventional ILS procedures at Indonesian airports with complex terrain. Without this evidence, PBN implementation decisions may rely on general expectations rather than airport-specific operational performance.

METHOD

This section compares conventional navigation and PBN, explains how flight simulation with BlueSky can be performed, how efficiency analysis parameters can be calculated and the conditions of Sam Ratulangi Airport, Manado.

Conventional navigation versus performance-based navigation

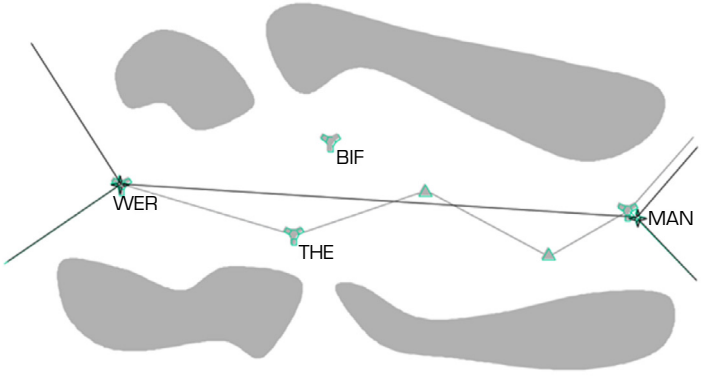
Flight navigation ensures safe and efficient aircraft movement between points, involving route planning, position monitoring, and fuel estimation as part of aviation operations regulated under the Law of the Republic of Indonesia No. 1 of 2009 concerning aviation. Conventional navigation relies on ground-based aids such as VOR, NDB, and ILS, which provide stable guidance but limit route flexibility, especially in complex terrain, see Fig. 1.



Source: ICAO (2023).

Figure 1. Conventional flight routes between navigation aids.

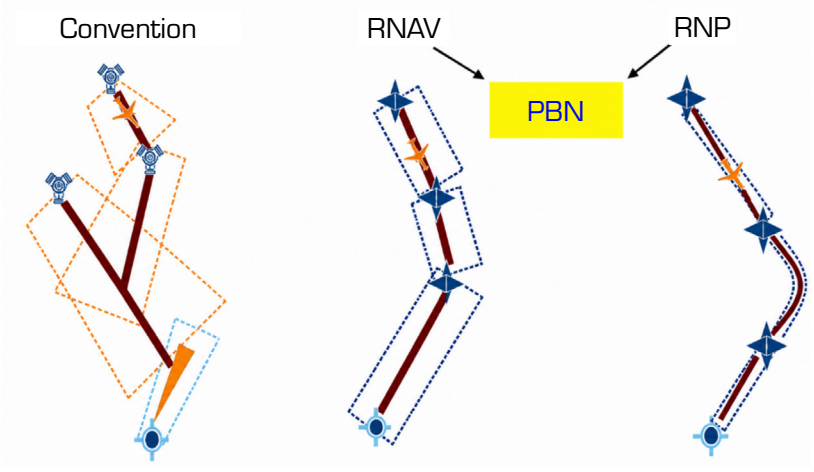
In area navigation, fixes were created by defining their name, latitude and longitude. The fixes allowed the design of routes to be less dependent on the location of navigation aids (NAVAIDs), so that the design could better accommodate airspace planning requirements (Fig. 2). The degree of flexibility in route design depends on the specific radio navigation system employed, such as distance measuring equipment (DME)/VOR or global navigation satellite system (GNSS). Additional advantages include the capability to store routes within a navigation database, which reduces pilot workload and promotes more consistent adherence to the nominal track. This method represents an improvement over conventional non-area navigation procedures, which are typically based on heading, timing, or DME arc techniques.



Source: ICAO (2023).

Figure 2. Area navigation procedure design.

PBN, introduced by ICAO, shifts from sensor-based to performance-based navigation, using area navigation capability and onboard performance monitoring to meet defined accuracy, integrity, continuity, and functionality requirements (ICAO 2016; Guo and Huang 2021), as shown in Fig. 3. Under ICAO Doc. 9,613, the numeric value in an area navigation system (RNAV) and RNP specifications denotes the required lateral navigation accuracy in nautical miles for at least 95% of the flight time. For example, RNAV 10 requires 10 NM accuracy, while RNP 1 requires 1 NM accuracy and additionally requires onboard performance monitoring and alerting.



RNAV: area navigation system; RNP: required navigation performance; PBN: performance-based navigation. Source: Guo and Huang (2021).

Figure 3. Difference in area tolerance of navigation tools.

PBN relies on an area navigation system (RNAV) consisting of three main components. The first component is the navigation application, which is tasked with identifying navigation needs based on the airspace concept, such as air traffic service routes and instrument approach procedures. The second component is the NAVAID infrastructure, which includes

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ground-based and satellite-based navigation aids needed to support navigation specifications. The last component is the navigation specification, which details the technical and operational functions required of RNAV equipment to meet specific airspace needs. These specifications are summarized in Table 1.

Table 1. RNAV and RNP navigation specifications in nautical miles (NM).

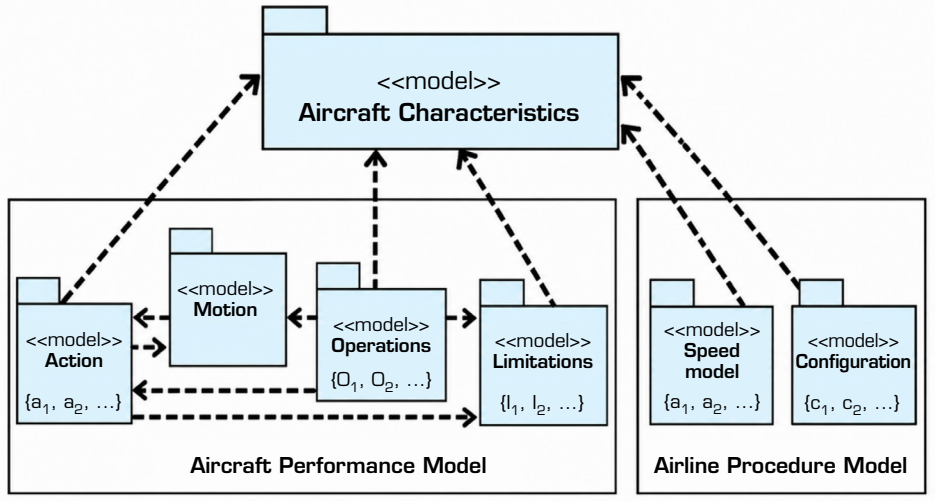
Navigation specification	En-route oceanic	En-route continental	Arrival	Approach				DEP
				Initial	Intermediate	Final	Missed	
RNAV 10	10							
RNAV 5		5	5					
RNAV 2		2	2					2
RNAV 1		1	1	1	1		1	1
RNP 4	4							
RNP 2	2	2						
RNP 1			1	1	1		1	1
Advanced RNP	2	2 or 1	1	1	1	0.3	1	1
RNP APCH				1	1	0.3	1	
RNP AR APCH				1–0.1	1–0.1	0.3–0.1	1–0.1	
RNP 0.3		0.3	0.3	0.3	0.3		0.3	0.3

RNAV: area navigation system; RNP: required navigation performance; APCH: approach; AR: arrival; DEP: departure. Source: ICAO (2016).

In Indonesia, PBN implementation began in 2019 under ICAO's Aviation System Block Upgrade roadmap, targeting airports with limited navigation facilities and complex terrain. Despite progress, challenges remain in harmonizing national policies with global standards and in demonstrating airport-specific operational benefits through quantitative evidence.

Flight simulation with BlueSky

BlueSky ATM Simulator, developed by TU Delft, is an open-source platform for modelling air traffic management and flow (Ongkowijoyo and Ruseno 2021). Its accessibility and flexibility make it suitable for academic research for evaluating navigation procedures, particularly when transparent assumptions and repeatable scenarios are required. BlueSky integrates the Base of Aircraft Data (BADA) from Eurocontrol, ensuring realistic aircraft performance modelling, as shown in Fig. 4.



Source: Schornagel (2022).

Figure 4. Base of Aircraft Data (BADA) performance model structure.

The simulator supports large-scale, real-time scenarios, and stochastic modelling, allowing randomization of variables such as aircraft speed to reflect operational uncertainty. In this study, BlueSky is used to simulate 1,000 aircraft performing conventional (ILS) and PBN-based (RNP) approaches at Sam Ratulangi International Airport. Speed distributions are generated using normal distribution based on FlightRadar24.

Compared to commercial tools like Simmod, AirTOp, and TAAM, BlueSky offers significant advantages for research: open-source access, customizable scripts, and integration with external datasets. These features enable unbiased and flexible evaluation of navigation procedures, making BlueSky an ideal choice for this study.

Efficiency analysis parameters

Three key parameters were selected to evaluate approach efficiency: flight distance, flight time, and fuel consumption.

Flight distance

Flight distance is measured from the initial STAR waypoint to runway touchdown using BlueSky simulation. Shorter distances reduce fuel burn and emissions, supporting operational and environmental goals (Fuel 2025). PBN-based routes are expected to minimize distance compared to conventional procedures.

Flight time

Flight time is defined as the airborne duration from STAR entry to landing (ICAO 2018). Reduced flight time improves operational efficiency and enables higher aircraft utilization. Simulation results will be visualized using boxplots for comparative analysis.

Fuel consumption

Fuel consumption is calculated based on distance and aircraft performance data from BADA 18 (Hassan *et al.* 2021; Kühn 2023). Fuel efficiency is critical as it accounts for up to 39% of airline operating costs. PBN procedures are anticipated to lower fuel consumption significantly, contributing to sustainability targets (Inderawan *et al.* 2024).

Sam Ratulangi International Airport, at Manado, Indonesia

Sam Ratulangi International Airport is identified by ICAO code WAMM and IATA code MDC. It is the second largest airport in Sulawesi and ranks among the busiest airports in Indonesia (Direktorat Jenderal Perhubungan Udara 2022). Located 13 km from Manado city center at an elevation of 328 ft, the airport serves domestic and international operations. Figure 5 presents the layout of manoeuvring area at Sam Ratulangi Airport.

In 2018, the airport recorded 2.7 million passengers and 25,914 aircraft movements, with projections reaching 48,966 movements by 2028 (Paendong *et al.* 2020). This growth underscores the need for efficient approach procedures to optimize capacity and reduce delays.

The airspace comprises Manado CTR (Class C, GND-10,000 ft, 30 NM radius) and Manado TMA (Class B, 10,000 ft-FL245). Terminal approach services are provided by Manado approach, while aerodrome control is provided by Ratulangi Tower. Current procedures include conventional ILS/VOR-based operations and RNP arrival/approach procedures for Runways 18 and 36 (Fig. 6) and corresponding Table 2 for details.

DATA PROCESSING AND SIMULATION

This section explains the collection of aircraft speed data, stochastic programming and simulation, as well as data extraction and processing.

Aircraft speed data collection

Aircraft speed data were obtained from FlightRadar24 (2025), which provides real-time flight information including ground speed, altitude, and route details. The study used ground speed because it is the speed directly available from the surveillance-derived dataset and is consistent with BlueSky trajectory-log processing. Data were filtered for STAR waypoints relevant to Sam Ratulangi Airport, including GOTSA, TEBAX, ONOTA, NOKOV, SOSOK, and LUANG.

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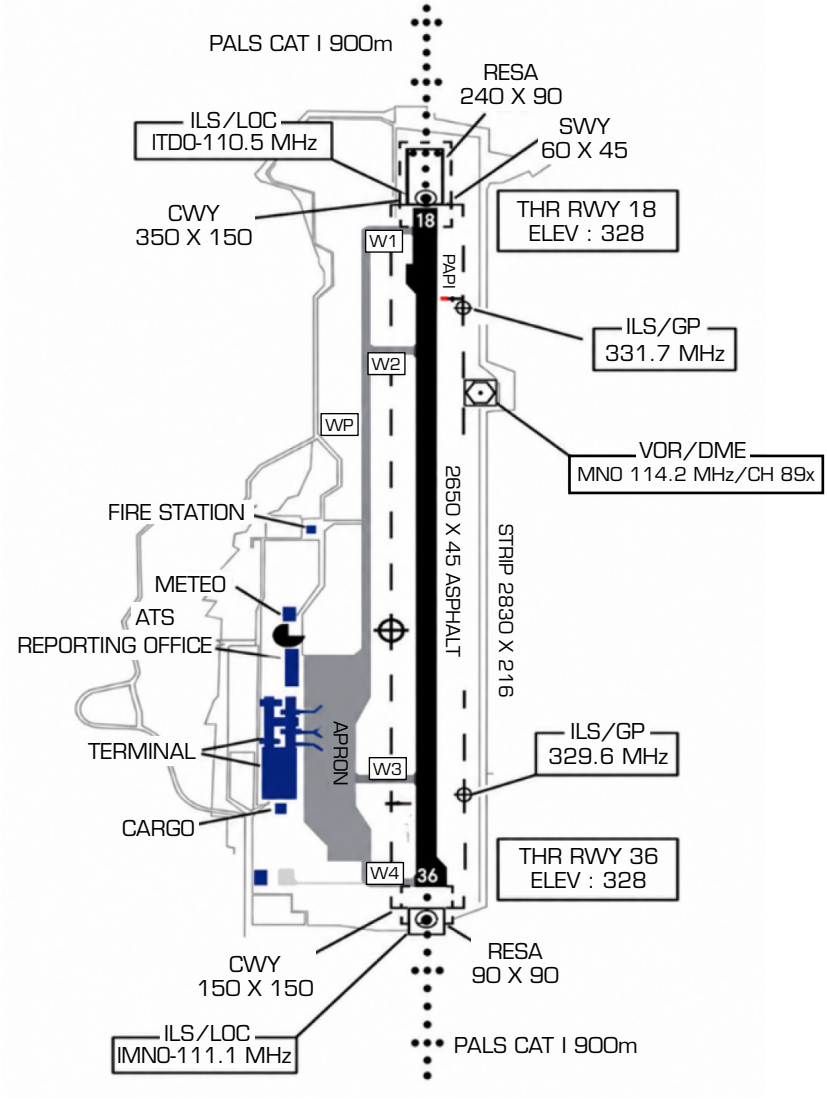


Source: Direktorat Jenderal Perhubungan Udara (2022).

Figure 5. Layout of manoeuvring area at Sam Ratulangi Airport, Manado, Indonesia.

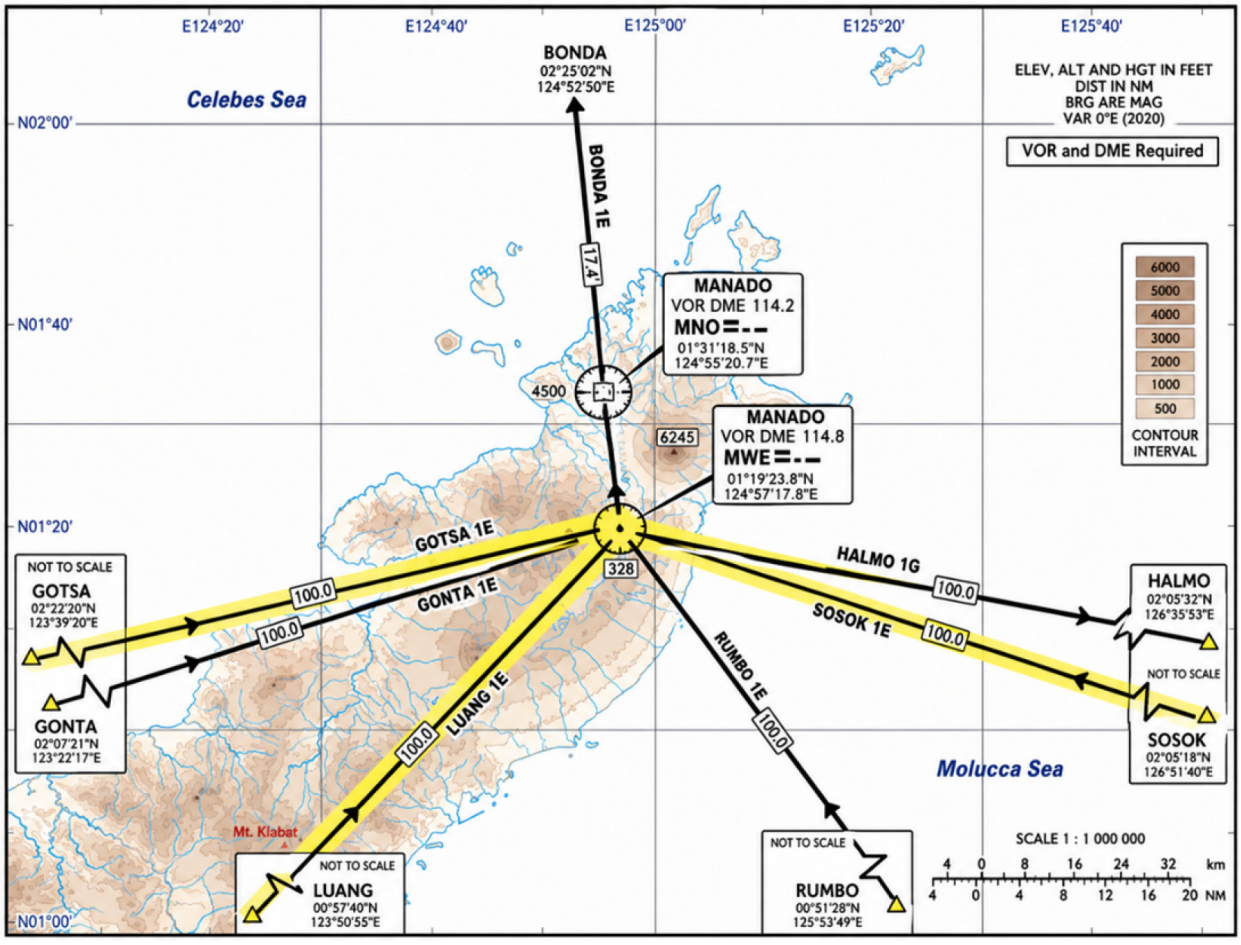
Statistical analysis was performed to calculate the mean speed (μ) and standard deviation (σ) at each waypoint (Eqs. 1 and 2):

$$\mu = \frac{\sum X_i}{n} \tag{1}$$

$$\sigma = \sqrt{\frac{\sum (X_i - \mu)^2}{n}} \tag{2}$$

Where: X_i: the observed ground speed; n: the number of observations.

These parameters represent operational variability and serve as input for stochastic simulation. For example, GOTSA shows higher average speed with low variability, while NOKOV exhibits wider dispersion (Fig. 7).



VOR: very-high frequency omnidirectional range; DME: distance measuring equipment.

Figure 6. STAR chart segment used to identify arrival fixes and procedure routing for Runways 18 and 36.

Table 2. Geographical coordinates of main fixes/waypoints used in the simulation*.

Fix/Waypoint	Latitude	Longitude	Use in this study
WAMM/MDC	01°32'57.34"N	124°55'33.61"E	Airport reference point
GOTSA	00°56'19.51"N	123°20'07.21"E	Arrival fix / STAR
TEBAX	01°05'47"N	123°38'11"E	Intermediate STAR fix
ONOTA	01°20'46"N	124°06'49"E	Intermediate STAR fix
NOKOV	01°48'25"N	124°39'07"E	Intermediate STAR fix
SOSOK	00°46'36.34"N	126°31'40.00"E	Arrival fix / STAR
LUANG	00°04'20.09"N	123°50'54.99"E	Arrival fix / STAR

*Coordinates are provided for simulation traceability and are not intended for operational navigation. Source: AirNav Indonesia Nav-Card waypoint database and airport-coordinate references.

The processed data ensure realistic simulation inputs and provide insights into traffic dynamics at Sam Ratulangi Airport. Statistics are presented in Table 3. The procedures evaluated in the simulation were the conventional ILS/VOR-based arrivals and the RNP STAR/IAC procedure set serving Runways 18 and 36. The STAR chart was used to identify the arrival fixes and route geometry, while the IAC was used to define the final approach alignment.

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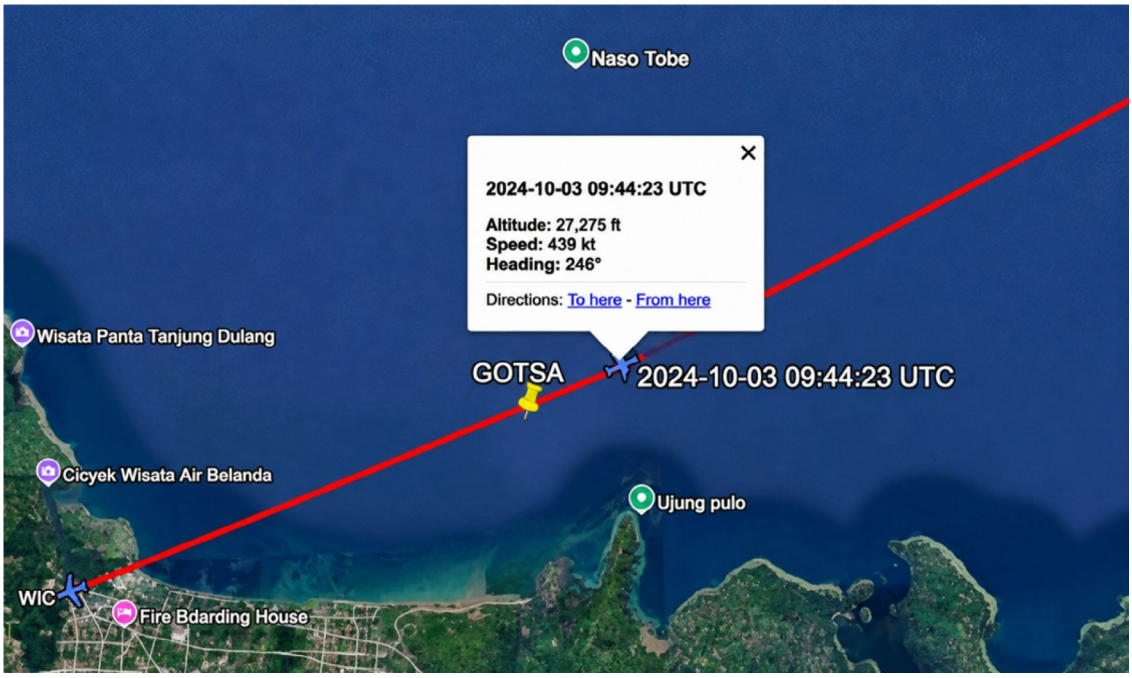

Figure 7. Real-time aircraft ground-speed data.

Table 3. Ground-speed data for each waypoint.

Waypoint	Sample No.									Average	Standard deviation
	1	2	3	4	...	...	18	19	20		
GOTSA	472	470	485	472	...	...	478	509	468	474.1	15.4
TEBAX	476	464	471	480	...	...	449	482	475	464.0	17.7
ONOTA	445	408	433	425	...	...	410	438	427	429.7	13.1
LEGUS	425	351	384	392	...	...	387	410	395	402.0	18.4
GOPRI	402	307	341	353	...	...	368	357	367	363.0	25.7
NOKOV	348	281	308	289	...	...	270	352	350	310.0	33.9
MULAN	319	252	314	270	...	...	242	286	284	279.7	22.9
MM601	283	272	309	276	...	...	251	283	280	275.8	17.3
MM602	272	262	271	271	...	...	219	286	241	258.6	21.4
MM603	239	229	247	243	...	...	172	202	230	220.3	21.0

Stochastic programming and simulation

After statistical analysis, random speeds were generated for each waypoint using a normal distribution (Eq. 3):

$$X = \mu + Z \cdot \sigma \tag{3}$$

Where: X: the simulated speed; μ: the mean; σ: the standard deviation; Z: a standard normal variable.

Python's numpy.random.normal() function was used, leveraging the Mersenne Twister algorithm for pseudo-random number generation. Figure 8 exemplifies the speed distribution result.

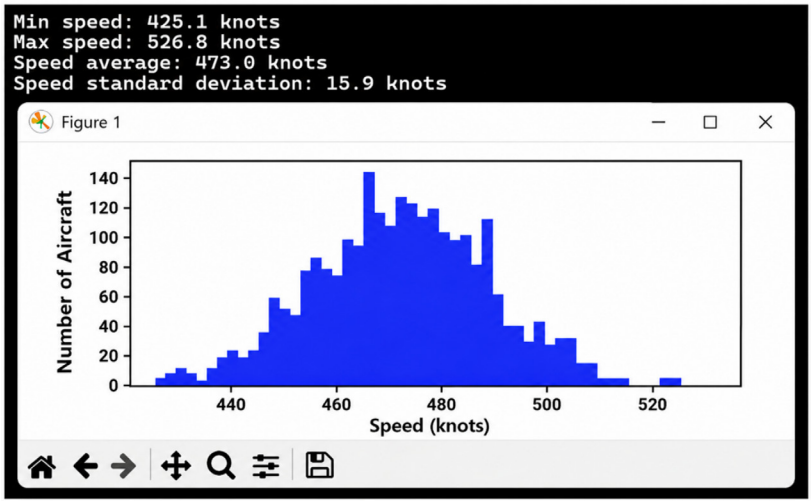

Figure 8. Aircraft ground-speed distribution at GOTSA.

A Python script automated scenario creation for 1,000 aircraft at each analyzed waypoint, incorporating waypoint coordinates, altitude constraints, runway assignment, and stochastic ground speeds. The simulated traffic was limited to A320-family jet aircraft, representing turbofan operations consistent with the BADA performance assumptions and the 150-seat fuel-consumption calculation used in this study.

Simulations were executed in BlueSky and divided into 20 sessions to manage log file limitations. Each session recorded flight paths, distances, and flight times, with outputs exported to Excel for further analysis. This workflow ensured repeatability and allowed direct comparison between ILS and RNP procedures for Runways 18 and 36. One example depicted in Fig. 9 presents a simulation via BlueSky ATM via GOTSA all the way to landing phase.

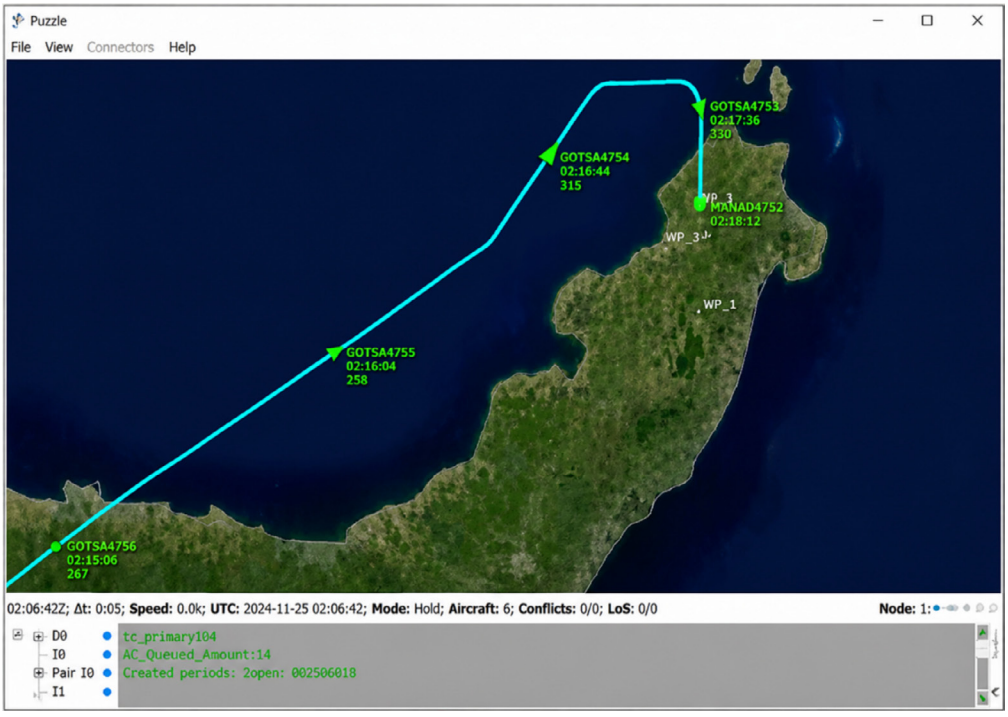

Figure 9. Approach-procedure simulation using BlueSky.

Data extraction and processing

Simulation outputs from BlueSky were exported as log files containing raw distance (m) and flight time (s) for each aircraft. Figure 10 shows six landing examples using waypoint GOTSA at four epoch times each. Fixed flight distance means the aircraft has already landed.

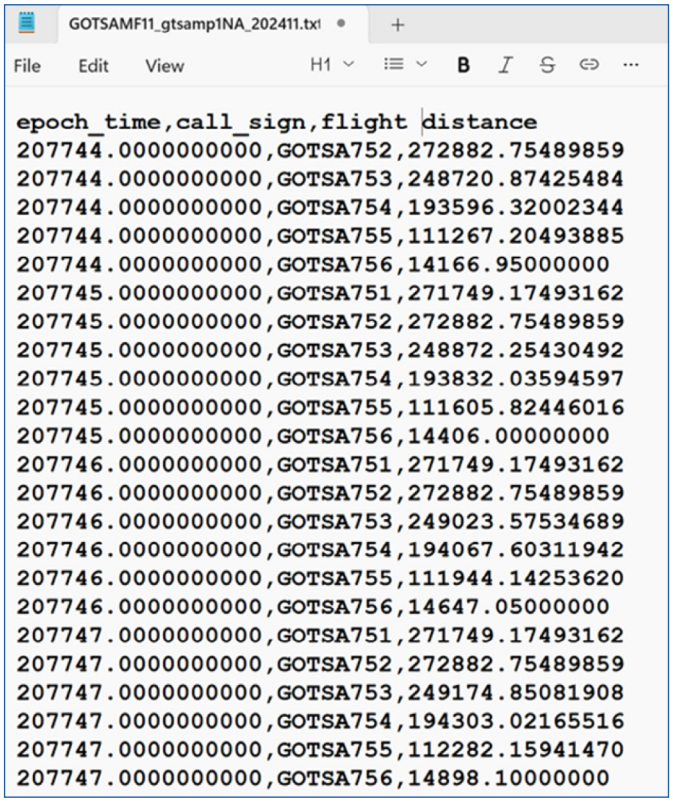

Figure 10. Simulation result log file.

As mentioned previously, 1,000 landings were conducted for each waypoint. The total distance and flight time for each flight were collected, organized and converted into compatible spreadsheet format. Table 4 presents nine examples of this data.

Table 4. Parameter conversion.

ID	Total distance (km)	Total time (minute)
GOTSA1	272.2	19.6
GOTSA10	272.6	19.5
GOTSA100	274.7	20.7
GOTSA1000	272.1	19.7
GOTSA101	273.0	20.2
GOTSA102	272.7	19.8
GOTSA103	274.5	20.3
GOTSA104	272.3	19.8
GOTSA105	274.7	20.3

Fuel consumption was calculated using the following simplified seat-based fuel-burn relationship (Eq. 4):

$$FC = Dist \times FBR \times nS \quad (4)$$

Where: *FC*: fuel consumption (kg); *Dist*: distance (km); *FBR*: fuel burn rate (0.02093 kg/km/seat); *nS*: seating capacity (150 seats) (Aircraft Commerce 2006, Kühn 2023).

Processed data were visualized using boxplots to compare distributions of distance, time, and fuel consumption between ILS and RNP procedures. Narrower distributions in RNP indicate higher consistency, while median values reflect overall efficiency.

RESULTS AND DISCUSSION

Although the STAR procedures at this airport include three arrival fixes (as shown in Table 2), each associated with two landing directions, the GOTSA-36 procedure is almost never selected by pilots. Therefore, only the other five procedures are included in the analysis below.

Distance analysis

Table 5 and Fig. 11 summarize the median distances for ILS and RNP procedures across five waypoints. RNP demonstrates superior efficiency at GOTSA and two waypoints on Runway 36 (SOSOK and LUANG). For GOTSA–Runway 18, RNP achieves a median distance of 272.1 km, 22.3 km shorter than ILS (294.4 km). At Runway 36, differences are more pronounced: RNP at SOSOK records 265.1 km *versus* 321.1 km for ILS (Δ = 56 km), while LUANG shows 258.6 km for RNP compared to 319.4 km for ILS (Δ = 60.8 km).

Table 5. Median distance values (km).

Waypoint	Runway	ILS	RNP	Differences
GOTSA	18	294.4	272.2	22.2
SOSOK	18	293.5	312.5	-19
LUANG	18	291.3	309.8	-18.5
SOSOK	36	321.1	265.2	55.9
LUANG	36	319.4	258.6	60.8

ILS: instrument landing system; RNP: required navigation performance.

Conversely, ILS outperforms RNP at SOSOK and LUANG for Runway 18, with median distances of 293.5 and 291.3 km, respectively, compared to RNP's 312.5 and 309.8 km. Boxplot visualization confirms these findings: RNP exhibits narrower distributions at waypoints where it excels, indicating higher consistency, while wider spreads for RNP at Runway 18 suggest greater variability.

These results showed that RNP offers significant distance savings mainly on Runway 36, where the RNP routes provide a more direct connection from the analyzed fixes toward final approach. In contrast, the Runway 18 RNP paths from SOSOK and LUANG are less favorable because the procedure geometry requires a longer transition around terrain and airspace constraints before alignment with final approach.

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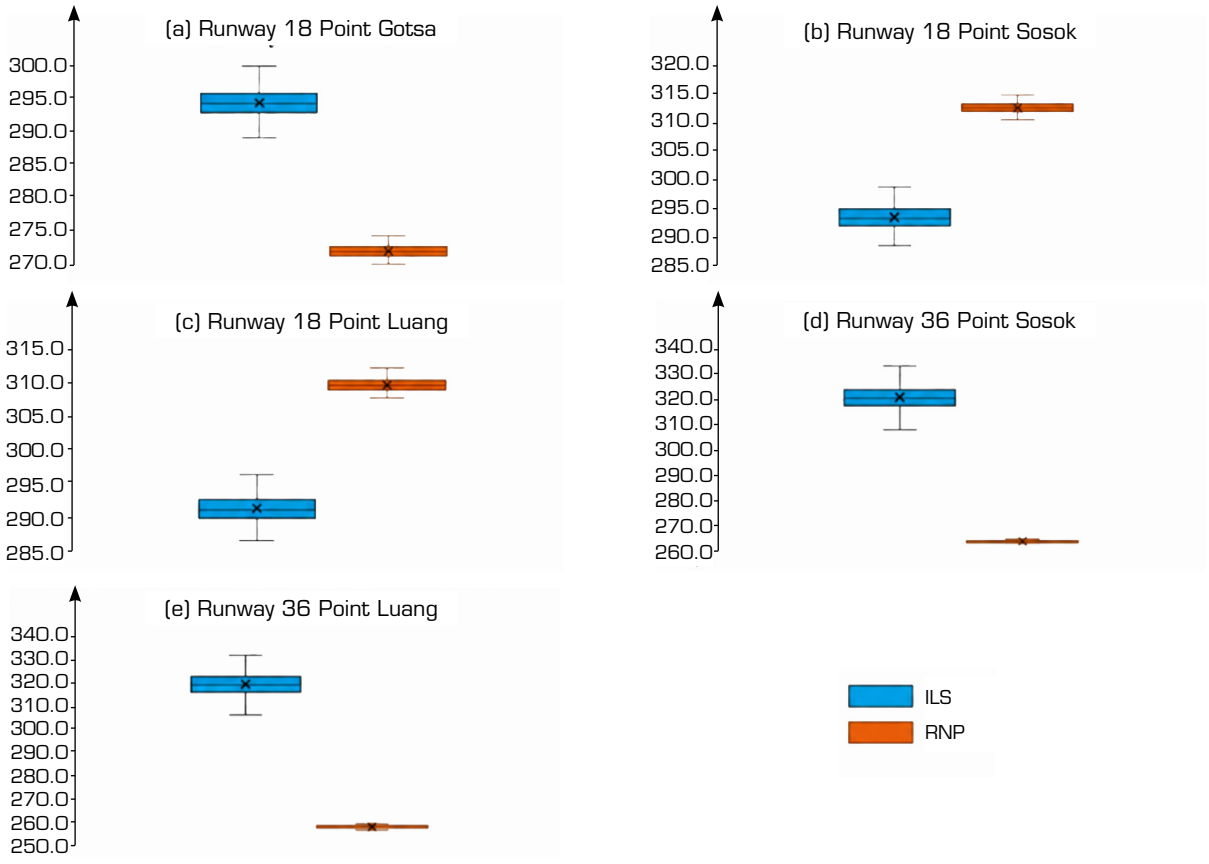


ILS: instrument landing system; RNP: required navigation performance.

Figure 11. Boxplot of distance travelled in km.

Flight time analysis

Table 6 and Fig. 12 present median flight times for ILS and RNP procedures. RNP demonstrates superior efficiency at GOTSA (Δ = 2.1 min faster) and at SOSOK and LUANG for Runway 36 (Δ = 2.4 and 2.5 min, respectively). These results confirmed that RNP-based approaches offer shorter travel times on routes with flexible airspace structures.

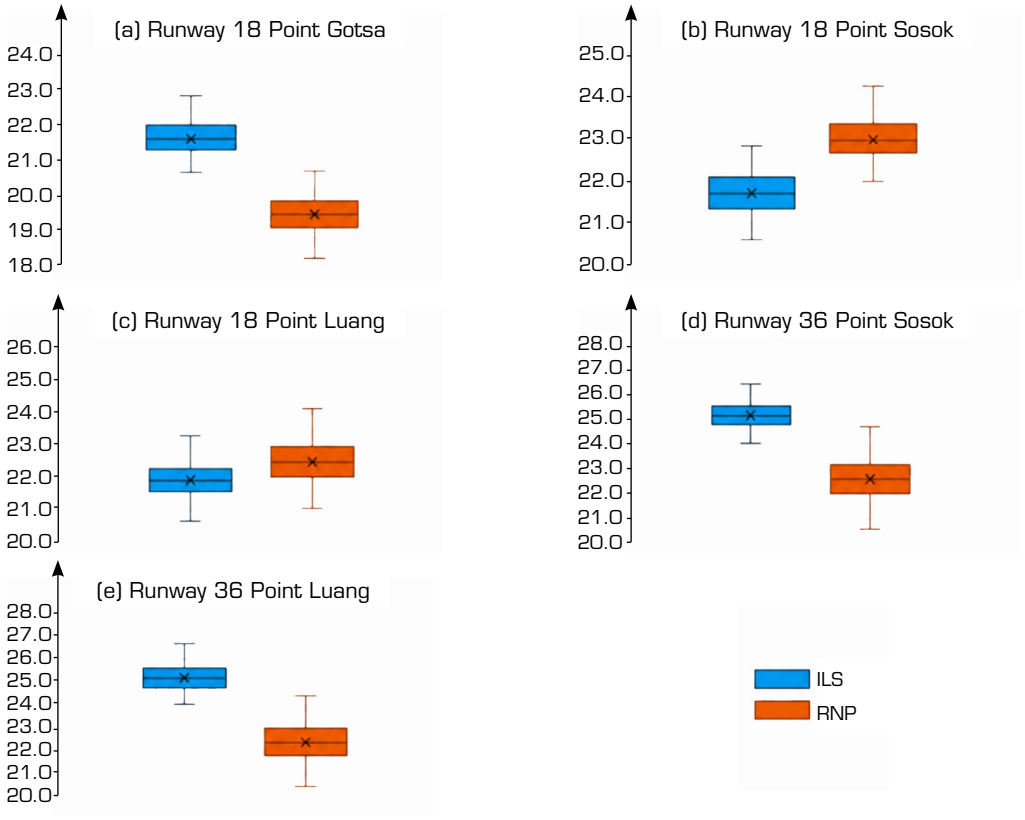
Table 6. Median travel-time values (minutes).

Waypoint	Runway	ILS	RNP	Differences
GOTSA	18	21.7	19.6	2.1
SOSOK	18	21.7	23	-1.3
LUANG	18	22	22.5	-0.5
SOSOK	36	25.2	22.8	2.4
LUANG	36	25.3	22.8	2.5

ILS: instrument landing system; RNP: required navigation performance.

Conversely, ILS outperforms RNP at SOSOK and LUANG for Runway 18, with median differences of -1.3 and -0.5 min, respectively. This suggests that certain approach paths remain more suitable for conventional procedures.

Boxplot visualization indicates narrower distributions for RNP, reflecting higher predictability and reduced variability, which are critical for sequencing and runway-throughput management.



ILS: instrument landing system; RNP: required navigation performance.

Figure 12. Boxplot of travel time (minutes).

Fuel consumption analysis

Table 7 and Fig. 13 present median fuel consumption for ILS and RNP procedures. RNP demonstrates significant efficiency gains at GOTSA (Δ = 70.1 kg), SOSOK (Δ = 175.8 kg), and LUANG (Δ = 190.9 kg) on Runway 36. These reductions translate into substantial operational and environmental benefits.

Table 7. Median fuel-consumption values (kg).

Waypoint	Runway	ILS	RNP	Differences
GOTSA	18	924.3	854.2	70.1
SOSOK	18	921.5	981.1	-59.6
LUANG	18	914.7	972.5	-57.8
SOSOK	36	1,008.2	832.4	175.8
LUANG	36	1,002.7	811.8	190.9

ILS: instrument landing system; RNP: required navigation performance.

Conversely, ILS outperforms RNP at SOSOK and LUANG for Runway 18, with savings of 59.6 and 57.8 kg, respectively. This suggests that route-specific characteristics influence the relative efficiency of navigation procedures.

Boxplot visualization indicates narrower distributions for RNP across most waypoints, reflecting higher predictability and operational stability. The fuel results also confirmed that shorter distance does not always translate proportionally into lower fuel burn because procedure geometry, speed profile, and runway direction affect the time spent in descent and maneuvering segments.

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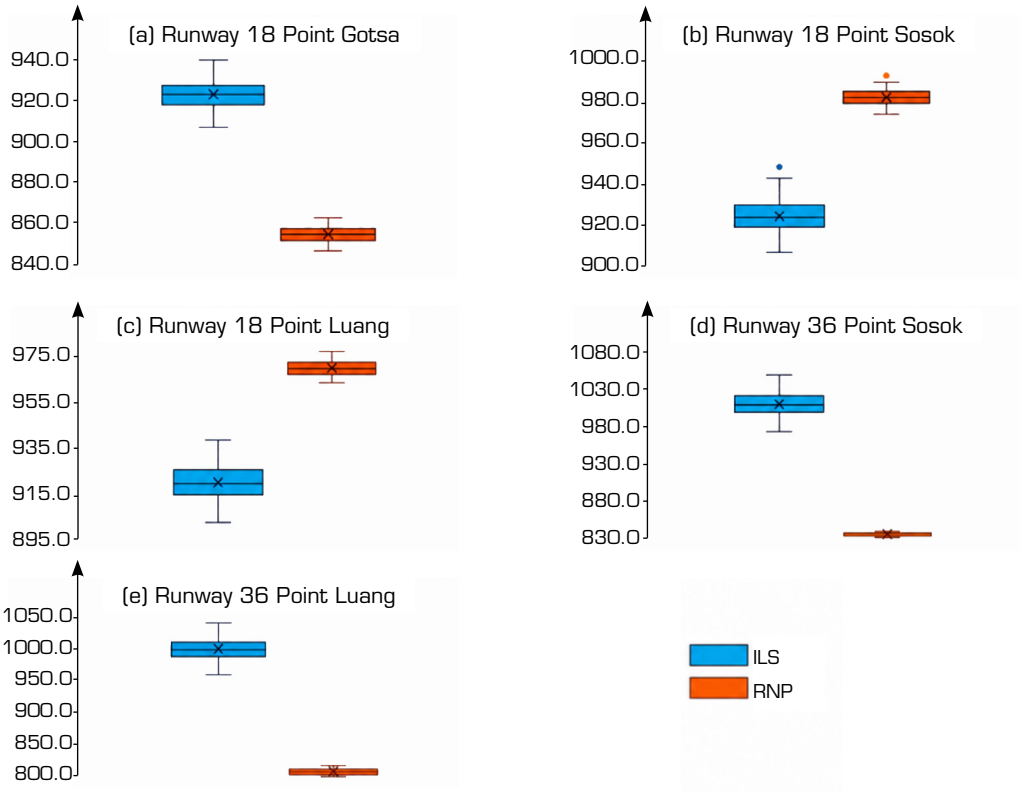

ILS: instrument landing system; RNP: required navigation performance.

Figure 13. Boxplot of fuel consumption (kg).

Combined analysis of distance, time, and fuel consumption

Prior to the combined analysis, a convergence analysis was performed to ensure a representative sample size. The analysis showed that 100 random samples were sufficient (relative error < 0.2%). However, simulations were continued with up to 1,000 aircraft per waypoint to increase reliability and reduce stochastic variability due to speed distributions or flight times. A larger sample size narrows the confidence intervals, allowing for greater validity of statistics such as the mean, standard deviation, and correlations between variables. Furthermore, the broader scope of operational conditions (approach routes, traffic patterns, and weather) makes the research results more relevant and generalizable to real-world conditions.

Based on the simulation data, the three variables (distance, time, and fuel consumption) exhibit a consistent relationship. The main patterns identified are:

- RNP excels in operational efficiency: Shorter flight distances and times directly contribute to fuel savings. Significant examples are seen at waypoints GOTSA and LUANG (Runway 36), with distance reductions of up to 60.8 km and fuel savings of up to 190.9 kg;
- ILS excels on certain routes: For example, at waypoints SOSOK and LUANG (Runway 18), ILS shows more efficient distance and time than RNP. This indicates that the RNP route design at these points is not optimal. Nevertheless, preference for RNP remains high due to its flexibility in dealing with dynamic conditions such as adverse weather and global policies encouraging the use of PBN.

Overall, the efficiency distribution of RNP is narrower, reflecting the consistency of satellite-based routes compared with procedures constrained by ground infrastructure. The runway-specific results indicated that Runway 36 benefits most from RNP because the arrival geometry is more direct from GOTSA, SOSOK, and LUANG. For Runway 18, ILS remains competitive at SOSOK and LUANG, suggesting that terrain avoidance, turn requirements, and existing procedure design can offset the theoretical efficiency advantage of RNP.

CONCLUSION

Based on the results and analysis, this study concluded that:

- The simulation of conventional approach procedures (ILS) and PBN (RNP) using BlueSky was successfully conducted. Although 100 random samples were sufficient, simulation with 1,000 aircraft is performed to increase reliability and reduce stochastic variability. This approach reflects real-world variability and provides robust data for comparative efficiency analysis;
- RNP procedures generally demonstrate superior efficiency in reducing flight distance and fuel consumption, particularly at waypoints GOTSA, SOSOK, and LUANG on Runway 36, achieving fuel savings of up to 190.9 kg and distance reductions of 60.8 km. However, certain routes on Runway 18 show ILS outperforming RNP in fuel efficiency by up to 59.6 kg. Despite this, RNP exhibits greater operational consistency with narrower data distribution, indicating higher predictability.

To build upon these findings, future research and development should focus on:

- Operational expansion: implement PBN procedures at airports with complex terrain to optimize efficiency and reduce controller workload while supporting carbon emission reduction. Extend similar analyses to other Indonesian airports to enhance generalizability;
- Procedure optimization: review and refine RNP designs for routes where efficiency remains lower than ILS, considering technical, operational, and geographical factors;
- Methodological enhancement: incorporate stochastic-based simulations in future studies to better capture real traffic variability and improve decision-making accuracy;
- Stakeholder collaboration: strengthen partnerships among air navigation authorities, airlines, and government bodies to promote data-driven policies for operational efficiency and sustainability.

These initiatives align with global strategies to advance PBN and reduce environmental impacts in aviation.

CONFLICT OF INTEREST

Nothing to declare.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable.

AUTHORS' CONTRIBUTION

Conceptualization: Indriyanto T., M'Azzuri B.Y.; **Data Curation:** M'Azzuri B.Y.; **Methodology:** M'Azzuri B.Y., Sembiring J.; **Formal Analysis:** M'Azzuri B.Y., Indriyanto T., Sembiring J.; **Investigation:** M'Azzuri B.Y., Sembiring J.; **Writing – Original Draft:** M'Azzuri B.Y.; **Writing – Review & Editing:** M'Azzuri B.Y., Indriyanto T., Sembiring J.; **Funding Acquisition:** Indriyanto T.; **Visualization:** M'Azzuri B.Y.; **Resources:** Indriyanto T., Sembiring J., M'Azzuri B.Y.; **Supervision:** Indriyanto T., Sembiring J.; **Software:** M'Azzuri B.Y.; **Validation:** Sembiring J.; **Final approval:** Indriyanto T.

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DECLARATION OF USE OF ARTIFICIAL INTELLIGENCE TOOLS

The authors declare that no artificial intelligence tools were used to generate the scientific content, analysis, or conclusions of this manuscript.

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