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Optimization of Indonesia's Pioneer Air Transport Network: Cost Efficiency under Capacity and Minimum Service Constraints for Airports in Papua

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Abstract

This study develops a two-stage optimisation model to evaluate Indonesia's pioneer passenger air transport network in Papua, including Dobo Airport in Maluku Province as a connected external node. The model addresses the need to improve public-service efficiency while preserving historical demand and satisfying airport capacity feasibility, belly cargo requirements, and minimum service levels for remote communities. The first stage applies a capacitated location-allocation formulation to assign spoke airports to existing hubs or selected potential hubs. The second stage optimises annual flight frequency on the resulting pioneer arcs under passenger capacity, belly cargo capacity, symmetric operation, and network-level load factor constraints. Network cost combines link operating cost and airport terminal cost, while commercial continuation is used as an availability indicator and emissions are evaluated after optimisation. Five scenarios were tested by varying minimum frequency and network load factor targets. The selected scenario reduces network cost from Rp649.32 billion to Rp603.96 billion, generating savings of Rp45.36 billion, or 6.99%. The average load factor increases from 74.84% to 90.28%. The optimised network serves all historical passenger demand without violating hub capacity constraints.

INTRODUCTION

Indonesia’s archipelagic geography continues to make air transport essential for connecting remote communities, particularly in Papua, where dispersed settlements, mountainous terrain, and limited surface transport alternatives constrain access to public services and regional economic centers. Pioneer aviation has therefore functioned not merely as a mobility service, but as a public policy instrument to maintain territorial accessibility and serve areas that are not commercially attractive (Tangkilisan, 2016). In Papua, this role also extends to logistics because air services support the movement of goods in areas where conventional transport alternatives remain limited (Yuliana et al., 2019). Similar experiences in remote regions show that air connectivity often requires public intervention when market-based services cannot provide adequate access (Fageda et al., 2018). However, this public service role creates a persistent planning tension: pioneer air services must be maintained to preserve accessibility, while their fiscal and operational performance must also be justified under thin and uneven demand conditions.

Within this context, the central problem is not whether pioneer routes are socially needed, but whether the existing network structure provides those services efficiently (Joshi et al., 2024; Kommaragiri, 2022; Ojha & Gupta, 2025; Priyadarshi, 2024). Budget realization records indicate that in 2024 passenger pioneer subsidies increased by 69.5%, while passenger realization increased by only 27.9%, suggesting that additional fiscal support was not translated into proportional service improvement. This condition points to a structural planning issue because low-demand air networks are sensitive to airport configuration, route distance, aircraft capacity, flight frequency, and load factor (Hoogreef et al., 2023; Resende et al., 2026). Hub-and-spoke planning is relevant because it allows dispersed flows to be consolidated and reduces reliance on excessive point-to-point operations (Pels, 2021). Yet network consolidation cannot rely only on administrative airport hierarchy, because feasible hub use also depends on capacity and flow allocation (Azizi & Salhi, 2022). Frequency is equally important because it determines capacity provision, operating cost, and minimum service availability (Durán-Micco & Vansteenwegen, 2022). Therefore, a planning approach is needed to evaluate Papua's pioneer passenger air network as an integrated public-service network that preserves minimum accessibility, improves operating-cost efficiency, respects capacity constraints, and recognizes the additional logistics role of belly cargo on passenger flights (Van Bockstaele et al., 2023).

The novelty of this research consists of several aspects. First, this study develops a two-stage optimization model specifically tailored to pioneer air transport networks, which differ fundamentally from commercial networks in their demand characteristics, service obligations, and operational constraints. Second, the model integrates capacitated location-allocation for hub selection with frequency optimization under multiple constraints (passenger capacity, belly cargo capacity, symmetric operation, network-level load factor, and minimum service frequency). Third, airport terminal cost is included as a node cost component, capturing the cost implications of concentrating activity at specific airports—an aspect often overlooked in link-focused models. Fourth, commercial continuation is used as an availability indicator rather than as an optimized service, allowing the model to leverage existing commercial connectivity without duplicating services. Fifth, the study conducts scenario analysis varying minimum frequency and network load factor targets to identify policy-relevant trade-offs between cost efficiency, service adequacy, and environmental performance. Sixth, emissions are evaluated post-optimization, providing environmental impact assessment without complicating the optimization objective.

The purpose of this study is to evaluate Indonesia's pioneer passenger air transport network in Papua through a two-stage optimization model that identifies cost-efficient network restructuring while preserving historical demand coverage, airport-capacity feasibility, belly cargo requirements, and minimum service for remote communities. The contribution of this research is the provision of a quantitative framework for pioneer air network planning that balances efficiency and public-service obligations, applicable not only to Papua but also to other remote regions in Indonesia and similar archipelagic countries. The specific objectives are: (1) to formulate and solve a capacitated location-allocation model for hub assignment and potential hub selection; (2) to optimize annual flight frequency under capacity, demand, and service constraints; (3) to compare multiple scenarios by varying minimum frequency and load factor targets; and (4) to evaluate the cost, operational, and environmental performance of the optimized network against the historical baseline. The benefits of this research are both theoretical (advancing the application of hub-and-spoke optimization to public-service aviation contexts) and practical (providing actionable insights for the Indonesian Ministry of Transportation to improve pioneer aviation subsidy efficiency).

METHOD

Model Formulation

This study formulates the pioneer passenger air transport network as a directed graph $G = (N, A)$, where airports are represented as nodes and flight legs are represented as directed arcs. Historical passenger demand is treated as a fixed service requirement, while route structure and annual service frequency are optimized to improve cost efficiency under capacity and minimum service constraints. Air network planning can be formulated as an optimization problem that links network structure with demand–supply interaction (Birolini et al., 2021). The use of hub-based consolidation is relevant because hub-and-spoke structures allow dispersed flows to be aggregated through selected hub nodes (Pels, 2021). Hub selection is constrained by capacity and flow allocation because a hub must not only be geographically suitable but also capable of absorbing assigned demand (Azizi & Salhi, 2022). Annual frequency is explicitly modeled because frequency determines capacity provision, operating cost, and service availability (Durán-Micco & Vansteenwegen, 2022).

The optimization is structured as a two-stage formulation. Model 1 determines the network structure by assigning spoke airports either directly to existing hubs or through selected potential hubs. Model 2 receives the network structure from Model 1 and determines annual flight frequency on the resulting pioneer arcs. This separation keeps the model computationally light. The notation used in the model formulation is described as follows.

i, j	: Airport node indices	r, h, k	: Existing hub, potential hub, and OD-pair indices
N	: Set of all airport nodes	N_P	: Set of pioneer spoke nodes
N_H^E	: Set of existing hubs	N_H^C	: Set of candidate potential hubs
A^P	: Set of pioneer arcs generated for optimization	A^{com}	: Set of available commercial continuation arcs
K^P	: Set of historical pioneer passenger OD pairs	P_k	: Restructured path for OD pair k
D_k	: Historical passenger demand for OD pair k	Q_{ij}^{pax}	: Passenger flow assigned to arc (i, j)
D_{ij}^{cg}	: Belly cargo requirement on arc (i, j)	C_{ij}^{op}	: Operating cost per flight on arc (i, j)
Cap_{ij}^{pax}	: Passenger capacity per flight on arc (i, j)	Cap_{ij}^{cg}	: Belly cargo capacity per flight on arc (i, j)
f^{floor}	: Minimum annual frequency if an arc is active	$\bar{f}_{ij}^{max}$	: Maximum annual frequency allowed on arc (i, j)
LF^{min}	: Minimum network average load factor target	W_i	: Demand weight assigned to node i
Cap_h^{hub}	: Available capacity of hub or potential hub h	I_h^{infra}	: Infrastructure eligibility of candidate hub h
Γ_{hr}^{com}	: Availability of commercial continuation from h to r	Ω_{hr}^P	: Feasibility of pioneer connector from h to r
F_i^{term}	: Terminal cost of active airport node i	β_0, β_1	: Intercept and slope of terminal cost function
y_{ir}^E	: 1 if spoke i is assigned directly to existing hub r	y_{ihr}^P	: 1 if spoke i is assigned through potential hub h to hub r

v_h	: 1 if candidate hub $h$is selected	b_{hr}	: 1 if potential hub $h$is connected to existing hub r
ρ_{hr}	: 1 if a pioneer connector $h-r$is required	$\hat{f}$	: Design frequency used in Model 1
z_{ij}	: 1 if pioneer arc $(i, j)$is active	f_{ij}	:Annual flight frequency on arc (i, j)

Airport terminal cost is included as a node cost component and charged once for each active node, not repeatedly for every arc. For an active node i, terminal cost is defined as:

$$F_i^{term} = \max(0, \beta_0 + \beta_1 f_i)$$

where node activity f_i is calculated from the annual frequency of incoming and outgoing pioneer arcs:

$$f_i = \sum_{j:(i,j)\in A^P} f_{ij} + \sum_{j:(j,i)\in A^P} f_{ji}$$

Model 1: network design and hub assignment.

Model 1 selects the hub-assignment pattern that minimizes the annual cost consequence of direct assignment, potential-hub assignment, pioneer connector formation, and flow-related arc formation. The objective is:

$$\min\ Z_1 = \sum_{i\in N_P} \sum_{r\in N_H^E} y_{ir}^E \,(C_{ir}^{op} + C_{ri}^{op})\hat{f}_{ir}^E + \sum_{i\in N_P} \sum_{h\in N_H^C} \sum_{r\in N_H^E} y_{ihr}^P \,(C_{ih}^{op} + C_{hi}^{op})\hat{f}_{ihr}^P$$
$$+ \sum_{h\in N_H^C} \sum_{r\in N_H^E} \rho_{hr}\,(C_{hr}^{op} + C_{rh}^{op})\hat{f}_{hr}^{\rho} + \sum_{(i,j)\in A^P} (\,C_{ij}^{op} + C_{ji}^{op})\hat{f}_{ij}$$

Each spoke must select one service pattern. A spoke may be assigned directly to an existing hub, assigned through a potential hub, or, if it is itself a candidate hub, selected as a potential hub:

$$\sum_{r\in N_H^E} y_{ir}^E + \sum_{h\in N_H^C} \sum_{r\in N_H^E} y_{ihr}^P + v_i = 1, \forall i \in N_P$$

where $v_i = 0$ for nodes that are not candidate potential hubs. Potential-hub assignment is allowed only when the candidate hub is selected and connected to an existing hub:

$$y_{ihr}^P \le v_h, y_{ihr}^P \le b_{hr}, v_h \le I_h^{infra}, \sum_{r\in N_H^E} b_{hr} = v_h$$

Hub capacity constraints ensure that assigned demand does not exceed available hub capacity:

$$W_h v_h + \sum_{i\in N_P} \sum_{r\in N_H^E} W_i\, y_{ihr}^P \le Cap_h^{hub} v_h, \forall h \in N_H^C$$

$$W_r + \sum_{i \in N_P} W_i\, y_{ir}^E + \sum_{i \in N_P} \sum_{h \in N_H^C} W_i\, y_{ihr}^P \leq Cap_r^{hub}, \forall r \in N_H^E$$

Connector feasibility is governed by the availability of commercial continuation or the feasibility of forming a pioneer connector:

$$b_{hr} \leq \Gamma_{hr}^{com} + \Omega_{hr}^P$$

$$\rho_{hr} \geq b_{hr} - \Gamma_{hr}^{com}, \rho_{hr} \leq 1 - \Gamma_{hr}^{com}, \rho_{hr} \leq \Omega_{hr}^P, \rho_{hr} \leq b_{hr}$$

The design frequency $\hat{f}$ is bounded by the minimum service requirement and by the two-direction capacity implication of symmetric operations:

$\hat{f} \geq f^{floor} x, x \in \{y_{ir}^E, y_{ihr}^P, \rho_{hr}\}$ and $\hat{f}_{ij} \geq \frac{Q_{ij}^{pax}}{LF^{min} Cap_{ij}^{pax}}, \hat{f}_{ij} \geq \frac{Q_{ji}^{pax}}{LF^{min} Cap_{ji}^{pax}}$

Model 2: route frequency and capacity optimization.

Model 2 receives the pioneer arc set A^P and restructured paths P_k from Model 1. Passenger flow is derived from historical OD demand and the path selected in Model 1:

$Q_{ij}^{pax} = \sum_{k \in K^P} D_k\, \delta_{ij}^k,$ $\delta_{ij}^k = \begin{cases} 1, & \text{if } (i,j) \in P_k \\ 0, & \text{otherwise} \end{cases}$

The objective of Model 2 is to minimize annual pioneer network operating cost, consisting of link flight cost and active airport terminal cost:

$$\min\ Z_2 = \sum_{(i,j) \in A^P} C_{ij}^{op} f_{ij} + \sum_{i \in N(A^P)} F_i^{term}$$

where $N(A^P)$ is the set of airport nodes touched by active pioneer arcs. The arcs generated by Model 1 are fixed as active in Model 2:

$$z_{ij} = 1, \forall (i,j) \in A^P$$

Annual frequency is bounded by minimum service and maximum feasible frequency:

$$f^{floor} z_{ij} \leq f_{ij} \leq \bar{f}_{ij}^{max} z_{ij}, \forall (i,j) \in A^P$$

Symmetric route operation is imposed on arc status and frequency:

$$z_{ij} = z_{ji}, \quad f_{ij} = f_{ji}$$

Passenger capacity and belly cargo capacity must be sufficient for assigned demand. Belly cargo is modeled as a capacity requirement attached to passenger flights because passenger aircraft belly capacity is an important component of air cargo supply (Van Bockstaele et al., 2023).

$Q_{ij}^{pax} \leq Cap_{ij}^{pax} f_{ij}, \forall (i,j) \in A^P$ and $D_{ij}^{cg} \leq Cap_{ij}^{cg} f_{ij}, \forall (i,j) \in A^P$

Finally, load factor is imposed as a hard constraint at the network level, rather than as an arc-level elimination rule. This treatment keeps the model consistent with the public-service nature of regional aviation, where level of service and social accessibility remain important even when individual routes have low utilization (Bråthen & Eriksen, 2018).

$$\sum_{(i,j)\in A^P} Q_{ij}^{pax} \geq LF^{min} \sum_{(i,j)\in A^P} Ca\,p_{ij}^{pax} f_{ij}$$

This constraint controls aggregate unused capacity while avoiding unrealistic enforcement of a minimum load factor on every thin-demand arc.

Data Acquisition and Preprocessing

The empirical analysis uses operational records of Indonesia's pioneer passenger air transport network in Papua, with Dobo in Maluku Province included as a connected external node because of its active route interaction with the Papua network. The dataset covers airport attributes, route records, passenger traffic, aircraft type, operating cost, airport operational cost, commercial route availability, and emission-related information. These data were transformed into airport nodes, directed flight arcs, historical passenger demand, annual service frequency, candidate hub attributes, commercial continuation indicators, and cost-related inputs. The spatial distribution of airports was first reviewed to define the study area and identify the geographic structure of the network because location and spatial interaction influence hub selection and network configuration (Lestary et al., 2024). Figure 1 presents the study area and airport node distribution, showing the position of spoke airports, existing hubs, and candidate potential hubs.

Figure 1: Study area and airport node distribution in Papua

Source: Author's analysis based on processed airport data.

The airports were classified into spoke airports, existing hubs, and candidate potential hubs based on Minister of Transportation Decree of the Republic of Indonesia No. KM 33 of 2024 concerning the National Airport System. Existing hubs were identified from airport hierarchy, while candidate potential hubs were screened using physical infrastructure feasibility. This screening prevents airports with insufficient infrastructure from being selected as local consolidation points. Capacity and feasibility are essential in hub-based network design because hub nodes must be able to absorb assigned flows and support consolidation functions (Azizi & Salhi, 2022). A candidate airport was considered eligible as a potential hub only if it met both runway and apron requirements:

$$I_i^{infra} = \begin{cases} 1, & \text{if } Runway_i \geq 1350 \text{ and } Apron_i \geq 10000 \\ 0, & \text{otherwise} \end{cases}$$

Route records were transformed into directed arcs and the existing route network was retained as the baseline structure for comparison and model input. Figure 2 illustrates the historical route network before optimization.

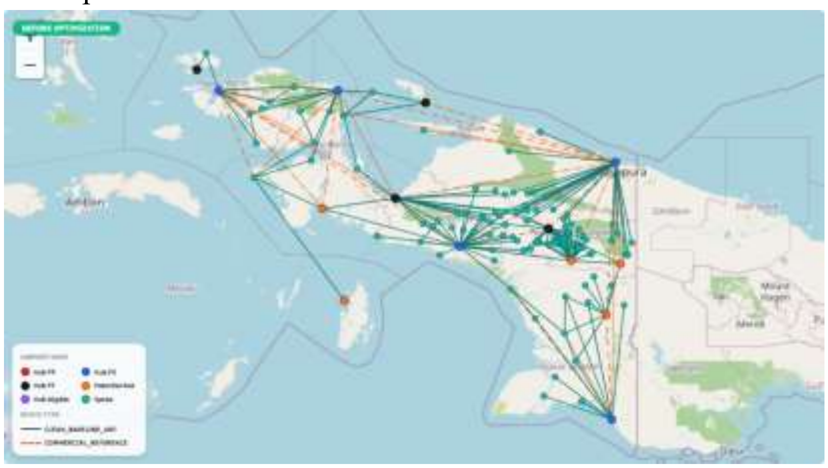

Figure 2: Existing air route network before optimization

Source: Author's analysis based on historical route data.

Route distance was calculated using Great Circle Distance based on the Haversine formula:

$$d_{ij} = 2R\arcsin\left(\sqrt{\sin^2\left(\frac{\varphi_j - \varphi_i}{2}\right) + \cos(\varphi_i)\cos(\varphi_j)\sin^2\left(\frac{\lambda_j - \lambda_i}{2}\right)}\right)$$

where d_{ij} is the distance between airports i and j, R is the earth radius, φ is latitude, and λ is longitude. The resulting distance was used as a consistent spatial measure for route representation and for subsequent distance-based cost and fuel-related calculations. Furthermore, the notations used in the data acquisition and preprocessing stages are defined as follows:

i, j	Airport node indices	t	Year index in historical records
$Runway_i$	Runway length of airport i	$Apron_i$	Apron area of airport i
I_i^{infra}	Infrastructure eligibility of airport i	d_{ij}	Great Circle Distance between airports $i$and j
R	Earth radius	φ_i, λ_i	Latitude and longitude of airport i

T_{ij}	Set of observed years for arc (i,j)	q_{ijt}	Passenger flow on arc (i,j)in year t
f_{ijt}	Frequency on arc (i,j)in year t	Q_{ij}^{hist}	Average historical passenger flow on arc (i,j)
f_{ij}^{base}	Average baseline frequency on arc (i,j)	$f_{ij}^{max,hist}$	Maximum observed historical frequency on arc (i,j)
$f_{ij}^{base,pair}$	Pair-adjusted baseline frequency	$f_{ij}^{max,pair}$	Pair-adjusted maximum frequency

Traffic records were filtered for pioneer passenger services and aggregated into annual average directed-arc demand. Frequency is retained because it links service intensity with capacity provision, which is central in network design and service planning (Durán-Micco & Vansteenwegen, 2022). For each observed directed arc (i,j), historical passenger flow, baseline frequency, and maximum historical frequency were calculated as follows:

$$Q_{ij}^{hist} = \frac{1}{|T_{ij}|}\sum_{t\in T_{ij}} q_{ijt}, \qquad f_{ij}^{base} = \frac{1}{|T_{ij}|}\sum_{t\in T_{ij}} f_{ijt}, \qquad f_{ij}^{max,hist} = \max_{t\in T_{ij}} f_{ijt}$$

Because the optimization imposes symmetric route operation, baseline and maximum frequency inputs were adjusted at the route-pair level:

$$f_{ij}^{base,pair} = \max\left(f_{ij}^{base}, f_{ji}^{base}\right), \qquad f_{ij}^{max,pair} = \max\left(f_{ij}^{max,hist}, f_{ji}^{max,hist}\right)$$

Passenger flow remains directional, so Q_{ij}^{hist} and Q_{ji}^{hist} may differ according to observed historical demand. Figure 3 visualizes the spatial concentration of historical passenger traffic, highlighting high-demand corridors and thin-demand areas that still require accessibility consideration.

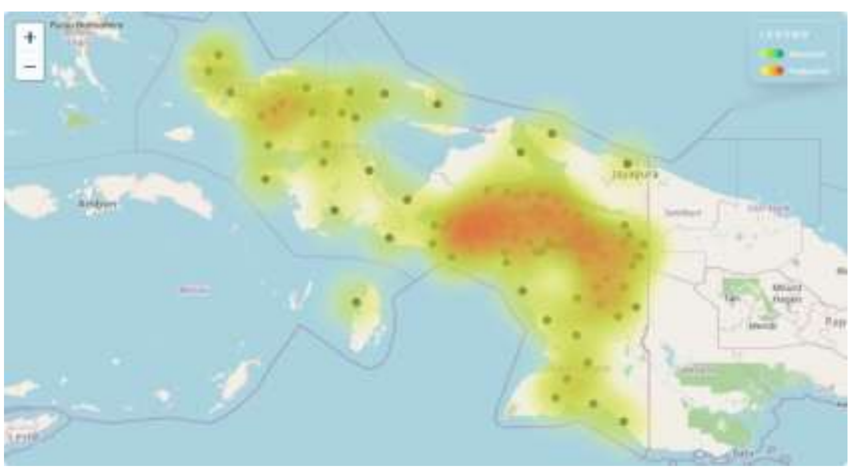

Figure 3: Historical passenger traffic heatmap in the study area

Source: Author's analysis based on historical pioneer passenger traffic data.

In addition, commercial route data were processed as continuation indicators rather than as optimized commercial services. A commercial connection indicates that a restructured pioneer path may continue through an available commercial leg, while the pioneer model only evaluates the pioneer segment.

Parameter Construction and Calibration

The preprocessed records were converted into model parameters representing aircraft capacity, belly cargo capacity, link operating cost, hub capacity, commercial continuation, airport terminal cost, and emission-related indicators. Aircraft type was retained as an exogenous attribute because it affects seat capacity, fuel consumption, and direct operating cost characteristics (Kühlen et al., 2023). For consistency across historical records, aircraft capacity was standardized by aircraft type using frequency-weighted observations. For aircraft type a, the standardized value of parameter x was calculated as:

$$\bar{x}_a = \frac{\sum_{r \in R_a} w_r \, x_r}{\sum_{r \in R_a} w_r}$$

where R_a is the set of observations for aircraft type a, x_r is the observed value, and w_r is the frequency weight. Furthermore, the notation used is defined as follows:

a	Aircraft type index	a_{ij}	Dominant aircraft type on arc (i, j)
r	Historical observation index	R_a	Set of observations for aircraft type a
x_r	Observed calibration value	w_r	Frequency weight of observation r
$Cap_a^{pax,std}$	Standard passenger capacity of aircraft a	$Cap_a^{cg,std}$	Standard belly cargo capacity of aircraft a
Cap_{ij}^{pax}	Passenger capacity per flight on arc (i, j)	Cap_{ij}^{cg}	Belly cargo capacity per flight on arc (i, j)
$FuelBurn_{ij}$	Fuel consumption per flight on arc (i, j)	b_{ij}^{fuel}	Fuel burn rate per kilometer on arc (i, j)
d_{ij}	Distance of arc (i, j)	P^{fuel}	Fuel price scenario parameter
C_a^{fixed}	Fixed or non-fuel cost per flight of aircraft a	C_{ij}^{fuel}	Fuel cost per flight on arc (i, j)
C_{ij}^{op}	Operating cost per flight on arc (i, j)	R_h^{comm}	Commercial passenger realization at hub h
TC_h	Terminal passenger capacity of hub h	Γ_{ij}^{com}	Commercial continuation availability on arc (i, j)
Cap_h^{hub}	Available hub capacity used in the model	f_i	Annual activity frequency at node i
F_i^{term}	Terminal cost of airport node i	τ_{CO2}	CO_2 emission factor
β_0, β_1	Terminal cost intercept and slope		

If a dominant value was clearly observed, a frequency-weighted mode was used instead of the weighted mean. This standardization was applied to passenger capacity and belly cargo capacity to avoid inconsistent interpretation of aircraft capacity across routes.

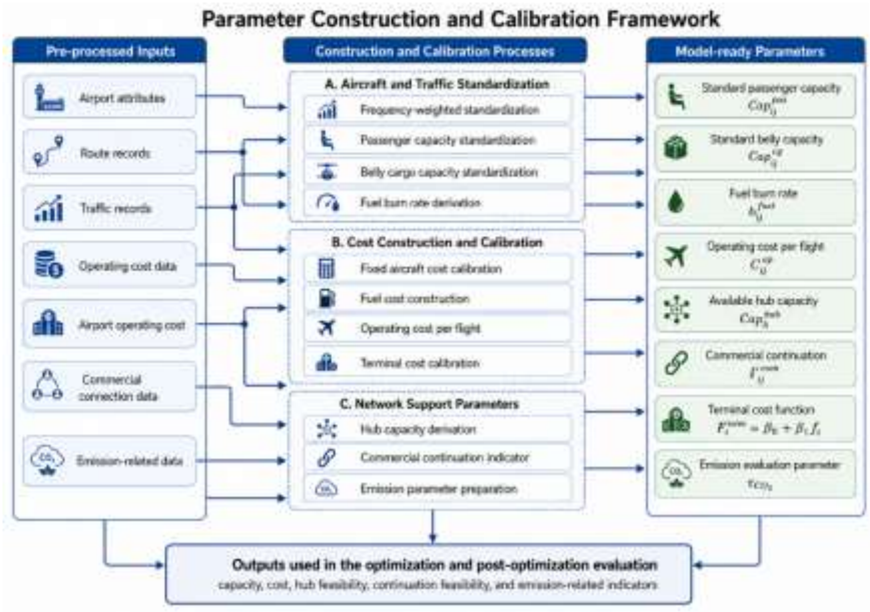

Figure 4: Parameter construction and calibration framework

Source: Author's analysis based on processed model inputs.

For each arc (i, j), standardized passenger and belly cargo capacities were assigned according to the dominant aircraft type:

$$Cap_{ij}^{pax} = Cap_{a_{ij}}^{pax,std}, \qquad Cap_{ij}^{cg} = Cap_{a_{ij}}^{cg,std}$$

Belly cargo was treated as a capacity requirement attached to passenger services, since passenger aircraft belly capacity represents an important component of air cargo supply when dedicated cargo services are limited (Van Bockstaele et al., 2023). Fuel burn rate was derived from fuel consumption per flight and route distance:

$$b_{ij}^{fuel} = \frac{FuelBurn_{ij}}{d_{ij}}$$

Link operating cost was constructed using calibrated operational cost rather than actual subsidy values. This distinction is important because subsidies may include contractual and administrative components that do not directly represent aircraft operating cost. The cost structure follows the direct operating cost perspective, where flight cost is represented by fuel and aircraft-related non-fuel components (Pohya et al., 2021). Fuel cost per flight was calculated as:

$$C_{ij}^{fuel} = d_{ij}\, b_{ij}^{fuel}\, P^{fuel}$$

The total operating cost per flight was then defined as:

$$C_{ij}^{op} = C_{a_{ij}}^{fixed} + C_{ij}^{fuel}$$

The fixed or non-fuel cost component C_a^{fixed} was calibrated by aircraft type from non-fuel operating cost observations. Small-aircraft operating cost studies support the need to distinguish cost parameters by aircraft type, particularly for regional and low-density operations (Marksel & Prapotnik Brdnik, 2023). The calibrated fixed cost values used for the pioneer passenger aircraft types in the model were Rp 10,710,941 per flight for Cessna 208B and Rp 5,130,571 per flight for PC-6.

Hub capacity was constructed from available terminal capacity after accounting for commercial passenger realization. This ensures that consolidated pioneer demand is assigned only to hubs or potential hubs with remaining capacity. Commercial connections were not modeled as residual capacity constraints. Instead, Γ_{ij}^{com} was used as an availability indicator showing whether a restructured pioneer path could continue through an existing commercial service. This treatment keeps the model focused on the pioneer passenger network while still recognizing existing commercial connectivity.

Airport terminal cost was introduced as a node cost component to capture the cost implication of airport activity generated by the optimized network. The terminal cost function was calibrated using a linear relationship between airport activity and operational cost. The calibrated equation used in the model was:

$$F_i^{term} = \max(0{,}1{,}873{,}309{,}791 + 1{,}181{,}837 f_i)$$

where f_i represents annual airport activity measured from incoming and outgoing flight frequency. The intercept is counted once for each active airport node, not repeatedly for every arc. Finally, emission-related parameters were prepared for post-optimization evaluation, not as part of the optimization objective or constraint, because air network configuration and operating frequency can affect fuel consumption and emissions (Sun et al., 2024). For each optimized arc, CO_2 emissions were evaluated as:

$$CO2_{ij} = b_{ij}^{fuel} d_{ij} f_{ij} \tau_{CO2}$$

RESULTS AND DISCUSSION

Scenario Setting and Performance

Five scenarios were evaluated to examine the trade-off between cost efficiency, capacity utilization, minimum service, and environmental performance. Each scenario $s \in S$ is defined by a scenario parameter vector:

$$\Theta_s = \left(LF_s^{min}, f_s^{floor}, P_s^{fuel}, p_s^{carbon}\right)$$

where LF_s^{min} is the minimum network load factor target, f_s^{floor} is the minimum annual frequency for active arcs, P_s^{fuel} is the fuel price, and p_s^{carbon} is the carbon price. In this study, P_s^{fuel} and p_s^{carbon} were fixed across all scenarios, while LF_s^{min} and f_s^{floor} were varied to test the balance between service adequacy and cost efficiency. The scenario set is expressed as:

$$S = \{S1, S2, S3, S4, S5\}$$

with the varied parameter pairs:

$$(LF_s^{min}, f_s^{floor}) \in \{(0.80,20), (0.85,24), (0.85,26), (0.90,26), (0.85,28)\}$$

and fixed parameters:

$$P_s^{fuel} = 28{,}000, p_s^{carbon} = 75$$

For consistency, the historical baseline was recalculated using the same fuel price assumption as the optimization scenarios. This ensures that the comparison reflects changes in network structure, frequency, capacity, and node activity rather than external price differences. In addition, to operationalize the proposed formulation, the optimization models were implemented in Python and solved using the Gurobi optimizer. Table 1 summarizes the scenario setting and optimization performance.

Table 1. Scenario setting and optimization performance

Scenario	LF_s^{min}	f_s^{floo}	Network cost (Rp billion)	Saving rate	Average LF	Total frequency	Capacity	Emission (million kgCO2)	Scenario meaning
Historical baseline	–	–	649.32	–	74.84%	–	252,436	8.21	-
S1	0.80	20	601.80	7.32%	90.86%	22,980	223,308	7.25	Maximum cost-efficiency / low service-floor benchmark
S2	0.85	24	604.96	6.83%	90.47%	23,206	225,352	7.32	Moderate service baseline
S3	0.85	26	603.96	6.99%	90.28%	23,156	224,732	7.31	Strengthened minimum-service test
S4	0.90	26	603.96	6.99%	90.28%	23,156	224,732	7.31	Policy-balanced selected scenario
S5	0.85	28	606.65	6.57%	90.02%	23,342	226,466	7.36	High minimum-service stress test

All scenarios produced lower network cost and higher average load factor than the historical baseline. Network cost decreased by approximately 6.57%–7.32%, while average load factor increased by about 15.18–16.02 percentage points. Total seat capacity decreased by approximately 10.29%–11.54%, indicating that the optimized networks reduced excess capacity while still accommodating historical passenger demand. Emissions also decreased by approximately 10.36%–11.70%, suggesting that operational efficiency and environmental performance moved in the same direction under the tested scenarios.

S1 produced the lowest cost, highest saving rate, highest average load factor, and lowest emissions among the tested scenarios. However, it applied the lowest minimum frequency requirement, making it less defensible from a minimum-service perspective. Furthermore, S4 was selected as the suboptimal policy solution for subsequent analysis. The term suboptimal refers to the best solution among the tested scenarios, not a claim of global optimality across all possible parameter combinations. S4 was selected because it balances cost efficiency, stronger minimum service, a higher network load factor target, and emission reduction.

Selected Network Structure

The selected solution produced a more consolidated pioneer network structure by assigning spoke airports to existing hubs or selected potential hubs. The optimized structure selected four potential hubs: Tanah Merah, Oksibil, Utarom, and Nop Goliat Dekai. These nodes were consistently selected across all tested scenarios, indicating 100% stability of potential-hub selection under the tested parameter variations. This result supports the hub-and-spoke principle that dispersed flows can be consolidated through selected hub nodes to improve network efficiency (Pels, 2021). The selection also reflects that potential hubs were not chosen merely by administrative status, but by their ability to support flow consolidation, capacity feasibility, and onward connectivity, which is consistent with capacitated hub-location logic (Azizi & Salhi, 2022).

Table 2. Selected potential hubs and optimized network roles

Selected potential hub	Optimized network role
Tanah Merah	Acts as the strongest local consolidation point among selected potential hubs.
Oksibil	Supports spoke consolidation around Oksibil and continuation toward Sentani.
Utarom	Supports connectivity around Kaimana/Fakfak and commercial continuation.
Nop Goliat Dekai	Supports spoke consolidation around Yahukimo and continuation toward Sentani.

The optimized network maintained full historical demand coverage, with 0% dropped demand. Compared with the historical baseline, the selected structure reduced total seat capacity by approximately 10.97% while increasing average network load factor by 15.44 percentage points. This indicates that the network restructuring did not reduce the public-service coverage of the pioneer system, but improved the alignment between historical passenger flow and supplied capacity. The resulting spatial configuration is shown in Figure 5.

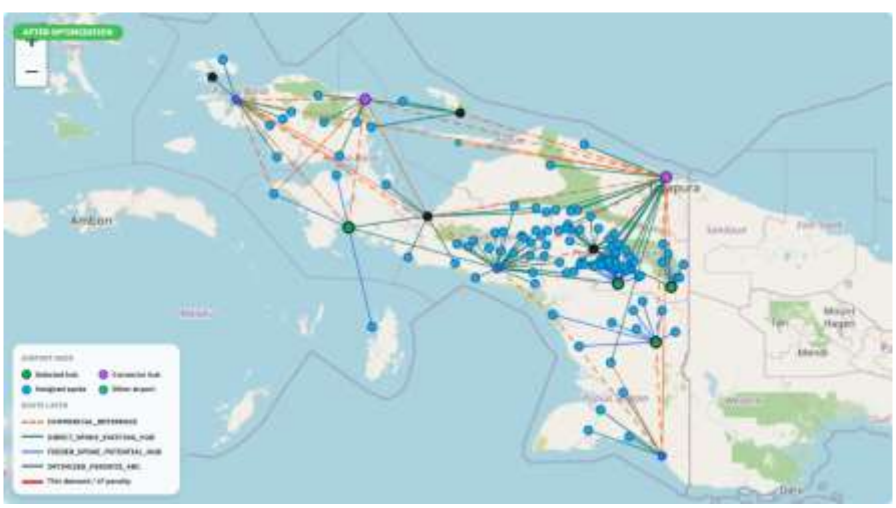

Figure 5: Optimized pioneer air transport network for the selected solution

Source: Author's analysis based on optimization results.

Hub Capacity and Commercial Continuation

The hub capacity audit confirms that the selected network remains feasible from the node-capacity perspective. No existing hub or selected potential hub exceeds its modeled annual capacity, indicating that the flow consolidation produced by the optimized network does not overload the receiving airports. This is important because hub selection in a capacitated network should account not only for spatial assignment but also for the ability of each hub to absorb allocated flows (Azizi & Salhi, 2022). Tanah Merah shows the highest utilization among selected potential hubs, while major existing hubs such as Sentani, Wamena, Douw Aturure, and Rendani remain well below their available capacity.

Figure 6: Hub capacity and utilization of the selected network

Source: Author's analysis based on optimization results.

Commercial continuation is used to complete several restructured OD movements after passengers reach an existing hub or selected potential hub. In the selected network, approximately 51% of historical passenger flow is associated with commercial continuation, showing that the optimized network does not rely only on new pioneer legs but also uses available commercial connectivity where applicable. These continuation legs are not charged as pioneer operating cost in the objective, because the model evaluates only the pioneer segments while reporting commercial continuation for transparency.

Figure 7: Commercial continuation flows in the selected network

Source: Author's analysis based on optimization results.

Overall, the capacity and continuation results indicate that the selected network is not only cost-efficient but also operationally feasible at the hub level and better integrated with existing commercial services.

Thin-Demand Routes

Although the selected solution achieves a high network-level average load factor, several individual routes still show low arc-level load factors. This result does not indicate a model failure because the load factor constraint is applied at the aggregate network level, not as a mandatory minimum for every route. In pioneer aviation, low-demand routes may still be retained when they provide basic accessibility for remote communities. Regional air service evaluation should therefore consider social accessibility and level of service, not only commercial utilization (Bråthen & Eriksen, 2018).

Figure 8: Thin-demand routes in the selected network

Source: Author's analysis based on optimization results.

Figure 8 presents the routes with the lowest load factor in the selected network. These routes represent the public-service trade-off of the optimized configuration: the model improves overall capacity utilization and cost efficiency, but still preserves access for very-low-demand areas. Therefore, thin-demand routes should be interpreted as accessibility-critical links that require policy attention, rather than as routes that should automatically be removed.

Discussion

The results show that cost efficiency in Papua's pioneer air transport network is not achieved merely by shortening routes, but by reorganizing how historical flows are consolidated, how frequency is supplied, and how capacity is used across the network. The selected solution reduces network cost while increasing the average load factor, indicating that the improvement comes from better alignment between fixed historical demand and supplied capacity. This is consistent with hub-and-spoke network logic, where dispersed flows can be consolidated through hub nodes to improve network efficiency under uneven demand conditions (Pels, 2021). The role of frequency is also central because frequency directly determines annual capacity, operating cost, and service availability (Durán-Micco & Vansteenwegen, 2022).

The selection of S4 reflects a policy-oriented balance rather than a purely lowest-cost solution. Although S1 produces the lowest cost, it applies the weakest minimum service requirement. S4 is more defensible because it maintains a stronger minimum service floor and satisfies a stricter network load factor target while producing the same result as S3. This distinction is important in pioneer aviation because regional air services cannot be evaluated only by commercial efficiency; they must also preserve accessibility and social service functions (Bråthen & Eriksen, 2018). Therefore, the persistence of several low-load-factor routes in S4 should not be interpreted as model failure, but as a consequence of maintaining access to very-low-demand areas.

The selected potential hubs—Tanah Merah, Oksibil, Utarom, and Nop Goliat Dekai—indicate the importance of local consolidation points in a geographically fragmented network. Their selection shows that potential hubs are not determined by administrative hierarchy alone, but by their ability to support assignment, capacity feasibility, and onward connectivity. This is consistent with capacitated hub-location models, where hub choice must consider flow allocation and available capacity (Azizi & Salhi, 2022). The hub-capacity audit further confirms that the optimized network remains feasible because no selected or existing hub exceeds its modeled capacity.

The inclusion of airport terminal cost strengthens the interpretation of network efficiency. Without node cost, the model could overemphasize link-level operating cost and understate the cost implication of concentrating activity at specific airports. By combining link operating cost and terminal cost, the model captures both flight-operation consequences and airport-activity consequences. This is aligned with direct operating cost approaches that represent flight cost through fuel and non-fuel aircraft-related components (Pohya et al., 2021). Commercial continuation also contributes to network efficiency by avoiding duplication of pioneer services on corridors already served commercially, although its reliability should be verified before operational implementation.

Finally, the emission reduction under S4 suggests that cost-efficient restructuring can also produce environmental co-benefits when frequency, excess capacity, and fuel-related operations are reduced. Network structure and operating frequency are relevant to aviation emissions because they affect total operations and fuel consumption (Sun et al., 2024). Nevertheless, the results should be read within the study limitations: the model does not perform full fleet assignment, uses historical rather than projected demand, and depends on scenario parameters such as fuel price, carbon price, load factor target, and minimum frequency. Future work should expand sensitivity testing, validate commercial continuation reliability, and incorporate more detailed aircraft assignment when operational data become available.

CONCLUSION

This study demonstrates that Indonesia's pioneer passenger air transport network in Papua can be restructured to improve cost efficiency while maintaining its public-service function. By integrating hub assignment, potential hub selection, annual frequency optimization, passenger and belly cargo capacity, airport terminal cost, commercial continuation, and a network-level load factor requirement, the model provides a quantitative framework for evaluating pioneer air services beyond route-by-route performance. Across the tested scenarios, all optimized networks reduced total network cost and improved average load factor compared with the historical baseline. The selected S4 scenario offers the most defensible policy balance because it maintains a stronger minimum service requirement, satisfies a stricter network load factor target, and produces the same operational outcome as S3. Under S4, total network cost decreases from Rp 649.32 billion to Rp 603.96 billion, generating a saving of Rp 45.36 billion or 6.99%, while average load factor increases from 74.84% to 90.28% and CO_2 emissions decrease from 8.21 million kgCO_2 to 7.31 million kgCO_2. The optimized network selects Tanah Merah, Oksibil, Utarom, and Nop Goliat Dekai as potential hubs, accommodates all historical passenger demand with no dropped demand, and remains feasible under modeled hub-capacity constraints. The results also show that cost efficiency does not require eliminating thin-demand routes, since several low-load-factor links remain necessary for accessibility. Overall, the findings suggest that hub-based restructuring, frequency adjustment, and integration with available commercial continuation can improve the efficiency of pioneer aviation, provided that minimum service, hub capacity, and remote-area accessibility remain protected.

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