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Analysis of the Operational Effectiveness of KM Sabuk Nusantara 37 on Pioneer Route R-3 from Teluk Bayur

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Abstract

This study evaluates the operational effectiveness of KM Sabuk Nusantara 37 on pioneer route R-3 from Teluk Bayur by integrating service quality, segment-level relative efficiency, transport demand, and vessel technical suitability. The analysis uses 2024 operational records, responses from 30 passengers, 2022–2024 traffic data, and ship-performance simulations. Service quality is measured as the difference between perceived and expected performance. Twenty-one route segments are assessed with an input-oriented CCR data envelopment analysis, using annual service-hours as the input and passengers and cargo as outputs. Mean perception is 4.0067 and mean expectation is 4.4217, producing an overall gap of −0.4150; reliability (−0.6333) and tangibles (−0.5667) require the greatest attention. Three segments form the relative-efficiency frontier: Teluk Bayur–Panasahan, Pulau Tello–Teluk Dalam, and Pulau Tello–Sigologolo. Panasahan–Sioban scores zero because it carried no traffic. Passenger load factors range from 0 to 15.58%, while cargo load factors range from 0 to 0.336%, confirming substantial spare capacity. Passenger demand in 2030 is estimated at 7,230–11,749 under three scenarios; cargo is not extrapolated because its short historical series has no significant linear trend. All evaluated loading conditions satisfy IMO intact-stability criteria. At 12 knots, resistance is approximately 61.1–61.6 kN, required power is 1,012–1,020 HP, and simulated pitch responses of 1.24°–1.47° remain below the adopted limit. Service improvement should therefore prioritize schedule reliability, port and onboard facilities, cargo consolidation, and demand-responsive frequency rather than additional vessel capacity.

Keywords: pioneer shipping; operational effectiveness; load factor; demand forecasting; seakeeping

1. INTRODUCTION

As an archipelagic state, Indonesia depends on maritime transport to connect economic centres with inhabited islands that are not commercially attractive. The national shipping framework assigns government a role in providing reliable inter-island connectivity [1], while pioneer shipping is specifically regulated as a fixed and regular public service for regions that are not served by commercial operators [2]. The policy is particularly relevant to disadvantaged, frontier, outermost, and border regions identified in the national development framework [3], [4]. In these areas, a pioneer ship functions as a lifeline: it enables access to education and health services, supports the movement of essential goods, and links local commodities to larger markets. Because demand is dispersed and often too low to recover operating costs, government support remains necessary. This condition is consistent with evidence that remote communities generally require public intervention to secure a minimum level of access to services, jobs, and markets [5].

A subsidy, however, does not by itself demonstrate that a service is effective. Effectiveness concerns the achievement of public-service objectives, whereas efficiency concerns the relationship between resources used and transport outputs produced. For pioneer shipping, the two concepts intersect through completed voyages, schedule adherence, passenger and cargo volumes, load factors, and the match between vessel capacity and demand on each segment. Indonesian studies have reported that pioneer services improve regional accessibility but continue to face uneven demand, schedule and infrastructure constraints, and low utilization on particular links [6]–[9]. An aggregate route total can conceal these imbalances because a busy segment may offset

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repeated empty sailings elsewhere. Segment-level evaluation is therefore required before an operating pattern is retained, modified, or rationalized.

Recent ferry research supports a multidimensional evaluation. Pham et al. combined principal component analysis and data envelopment analysis (DEA) to evaluate ferry-route efficiency while accounting for passenger mobility burdens [10]. Socially appropriate service frequency depends on stochastic demand and fixed vessel size [11], while later work demonstrated that tender design can affect operating costs and market structure [12]. Capacity assessment must also compare the supplied capacity with user benefits, user costs, and the cost of public provision [13]. These studies caution against interpreting a low load factor as an automatic reason to discontinue a lifeline service; utilization must be read alongside accessibility, service obligations, and feasible alternatives.

Island settings further require attention to service level and network structure. Hunt et al. assessed small-island connections using traffic volume, frequency, reliability, speed and travel time, vessel suitability, port conditions, and landside access [14]. Lau et al. showed that service frequency and port centrality can distinguish backbone links from subnetworks that require different interventions [15]. Indonesian evidence likewise highlights the importance of integrating sea transport with local distribution systems and economic activity rather than evaluating ships as isolated assets [16], [17]. These findings support mapping performance for every port-to-port segment and tailoring intervention to the social and logistical function of each call.

Operational productivity must also be reconciled with technical operability. Port-time reductions can create scope for lower transit speeds without reducing the offered service, thereby lowering energy use [26]. Resistance and power rise nonlinearly with speed, and propulsion data can be used to identify more efficient loading patterns [27]. For passenger vessels in Indonesian waters, seakeeping assessment should consider motions and accelerations against explicit comfort or operability criteria [25]. Operability additionally depends on wave height and period, vessel speed, heading, and the selected motion limit [28]. A capacity conclusion is therefore defensible only when operational demand is assessed together with resistance, propulsion, intact stability, and motion response.

Teluk Bayur is a pioneer-shipping base in West Sumatra that connects the mainland with islands in and around the Mentawai region. In 2024, the base served routes R-3 and R-4; this study focuses on KM Sabuk Nusantara 37 on route R-3. The 2024 operating evaluation indicates marked differences in passenger and cargo demand between calls, incomplete utilization of the available capacity, and service-quality expectations that were not fully met [18]. These conditions create a practical need to identify which segments use service resources productively, whether the vessel remains adequate for future demand, and which corrective measures are compatible with the social mandate of pioneer shipping.

Previous studies have generally examined route efficiency, service quality, network configuration, contracting, demand, or vessel operability as separate problems. Consequently, their results do not show whether a segment with low traffic is operationally inefficient, socially indispensable, technically constrained, or simply supplied with excessive capacity. This separation is particularly limiting for subsidized Indonesian pioneer shipping, where commercial utilization and minimum-access obligations must be evaluated simultaneously. The novelty of this study is an integrated, segment-based analytical framework that links five complementary components: user-perceived service gaps, input-oriented CCR-DEA efficiency, passenger and cargo load factors, demand scenarios, and vessel technical suitability. Each component answers a different management question, while their combined interpretation distinguishes service-quality deficiencies from capacity mismatch and technical limitations. Applied to all 21 segments of route R-3, the framework produces a traceable basis for frequency adjustment and route review without treating a low-output segment as an automatic candidate for closure. The objectives are therefore to assess the operating condition and effectiveness of route R-3, determine whether KM Sabuk Nusantara 37 can sustain the required service, and formulate improvements for underperforming segments.

2. METHODS

This quantitative descriptive study examines KM Sabuk Nusantara 37 on pioneer route R-3 from Teluk Bayur. The operational unit of analysis is each of the 21 port-to-port segments in a 1,027-nautical-mile round voyage. Primary and secondary data comprise field observations, interviews, questionnaires completed by 30 service users, the 2024 Teluk Bayur operating evaluation [18], passenger and cargo records for 2022–2024, and vessel-simulation outputs. The vessel has a length overall of 62 m, breadth of 12 m, depth of 4.2 m, design

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draught of 2.7 m, deadweight of 500 t, capacity of 400 passengers and 50 t of cargo, and installed main-engine power of 1,500 kW.

2.1. Operational-effectiveness indicators

Questionnaire validation was conducted before the gap calculation. Item content was mapped to the five service-quality dimensions and reviewed for clarity, relevance to pioneer-shipping operations, and consistency with the indicators used in maritime passenger-service studies [19], [20]. The 30 returned questionnaires were then screened for completeness and response consistency; incomplete forms were excluded from calculation. Because the survey is intended to diagnose service priorities for this route rather than to estimate population-wide causal effects, the results are interpreted descriptively and are not generalized beyond the observed users. This scope is also consistent with the relatively small sample size. Service quality is evaluated using gap analysis equation 1,

$$G = P - E \tag{1}$$

where P is the mean perception score and E is the mean expectation score on a five-point Likert scale. The questionnaire covers tangibles, reliability, responsiveness, assurance, and empathy. A negative value means that perceived performance remains below user expectations. The approach is consistent with multidimensional passenger-transport service-quality research [19] and its application to Indonesian ferry or port services [20].

Relative segment efficiency is estimated using the input-oriented constant-returns-to-scale CCR DEA model introduced [21] and subsequently applied to ferry-route assessment [10]. Each segment is treated as a decision-making unit. The input is annual service-hours, calculated as sailing frequency multiplied by sailing-plus-port time, while the outputs are passengers and cargo. An input orientation is selected because route managers can more directly adjust controllable operating resources—particularly service time, frequency, and port-time allocation—than they can increase passenger or cargo demand in the short term. The model therefore estimates the proportional reduction in service-hours that would be possible while maintaining observed transport outputs. The CCR specification provides a common proportional benchmark for segments served by the same vessel and operating system; however, its constant-returns-to-scale assumption means that the score should be interpreted as relative operational productivity, not as a complete measure of social value or optimal subsidy.

For segment o, the multiplier form maximizes in equation (2) subject to $v \times o = 1$, for every segment j in equation (3), and non-negative weights. The equation (2) and (3) as follows:

$$u_1 u_1 o + u_2 u_2 o \tag{2}$$

$$u_1 u_1 j + u_2 u_2 j - \text{vxj} \leq 0 \tag{3}$$

The resulting score ranges from zero to one. A score of one denotes a frontier segment relative to this dataset; it does not establish that every public-service objective has been achieved. DEA is invariant to a consistent change in the scale of an output, so expressing all cargo observations in kilograms rather than tonnes does not alter the relative score.

Load factors are calculated separately for the two capacity types. Passenger load factor is in equation (4), and cargo load factor is in equation (5).

$$LFp = \frac{P}{(F \times 400)} \times 100\% \tag{4}$$

$$LFc = \frac{C}{(F \times 50000)} \times 100\% \tag{5}$$

where P is annual passengers, C is annual cargo in kilograms, and F is completed sailings. The denominators use the vessel capacities of 400 passengers and 50,000 kg per sailing. Passenger and cargo factors are not averaged because they represent different physical capacities. Cargo entries in the source table are treated consistently as kilograms, as specified for this analysis.

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2.2. Transport-demand Scenarios

Passenger demand is reported as scenarios rather than as one deterministic forecast. The low scenario holds 2024 demand constant; the base scenario applies the linear trend $\hat{Y}=5{,}637.667+538.500X$; and the high scenario compounds the 2022–2024 passenger growth rate of 8.39% per year. Scenario use is appropriate where service decisions must remain robust to uncertain demand [22]. These scenarios assume that the route definition, service policy, fares, population-access needs, and major economic conditions remain broadly comparable to the observation period. They do not incorporate structural breaks, new competing services, port closures, disasters, or policy-driven changes in demand. Cargo is not extrapolated because its three annual observations fluctuate and the fitted linear coefficient is not significant ($p=0.977$). Accordingly, passenger figures are planning scenarios rather than statistical prediction intervals, and no cargo point forecast is used for capacity decisions.

2.3. Vessel Technical-Suitability Assessment

Technical suitability is examined through resistance and power, intact stability, and seakeeping. Resistance is interpreted using the speed–resistance–power dataset and the established principles of the Holtrop–Mennen method [23]. Intact-stability outputs for four loading conditions are checked against the applicable area-under-GZ, maximum-GZ, angle, and initial-GM requirements of the IMO Intact Stability Code [24]. The model assumes an intact, clean hull; the specified loading distributions; calm-water resistance; and unchanged principal dimensions and propulsion characteristics. The base seakeeping simulation uses a JONSWAP spectrum, characteristic wave height of 2 m, modal period of 8.948 s, vessel speed of 12 knots, displacement volume of 1,207.274 m^3, and GMt of 3.433 m. It does not represent seasonal wave scatter, extreme weather, wind and current interaction, hull fouling, damage stability, machinery degradation, or every operational heading. A source worksheet labelled “beam seas” lists a 180° wave heading; therefore, response values are interpreted using the numerical heading and are not generalized by the textual label. The simulations support comparative technical assessment under the specified conditions and are not a substitute for full-scale trials or class-approved design verification.

3. RESULTS AND DISCUSSION

3.1. Operating Conditions and Service-quality Gaps

Route R-3 contains 21 segments operated at 28–29 sailings in 2024. Segment time is based on an ideal speed of 8 knots plus six hours in port. Teluk Dalam–Sibolga and its reverse are the longest segments at 97 nautical miles and 18.13 hours including port time. Demand is highly uneven: Panasahan–Sioban recorded neither passengers nor cargo, whereas Pulau Tello–Sigologolo carried 1,745 passengers and Teluk Bayur–Panasahan recorded the largest cargo quantity, 4,878 kg.

Table 1. Service-Quality Gap Analysis (n=30)

Dimension	Perception	Expectation	**GAP**
Tangible	–	–	−0,5667
Reliability	–	–	−0,6333
Responsiveness	–	–	−0,3083
Assurance	–	–	−0,3417
Empathy	–	–	−0,2250
Overall	4,0067	4,4217	−0,4150

As in Table 1 the mean perception score of 4.0067 indicates favorable user ratings, but it remains below the expectation score of 4.4217. Every dimension has a negative gap. Reliability is the first priority, particularly schedule consistency and trustworthy information, followed by tangibles such as onboard and port facilities. Empathy has the smallest shortfall, suggesting that staff interaction is comparatively close to expectations. Similar transport research warns that reliability and travel-time uncertainty directly affect the attractiveness of ferry services [29].

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3.2. Relative Efficiency and Load Factors

The CCR model places three segments on the relative-efficiency frontier: Teluk Bayur–Panasahan, Pulau Tello–Teluk Dalam, and Pulau Tello–Sigologolo. Sigologolo–Pulau Tello (0.734), Teluk Dalam–Pulau Tello (0.790), Sibolga–Teluk Dalam (0.675), and Sigologolo–Air Bangis (0.640) also show comparatively strong output per service-hour. Panasahan–Sioban scores zero because it produced no passenger or cargo output. Eight further segments score below 0.10, including low-demand return links toward Panasahan and Teluk Bayur as shown in Figure 1. These scores rank relative productivity within the observed route; they do not monetize the accessibility benefit of a call.

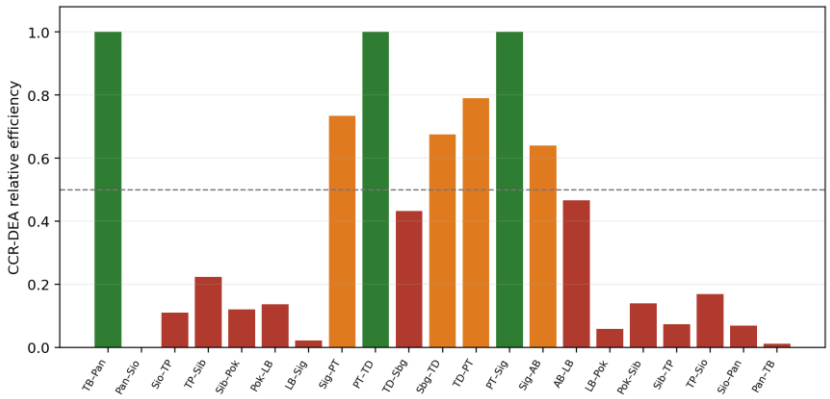


Figure 1. CCR-DEA Relative Efficiency for the 21 Route R-3 Segments

Load factors confirm substantial unused capacity. The maximum passenger load factor is 15.58% on Pulau Tello–Sigologolo, followed by 14.61% on Sibolga–Teluk Dalam and 13.57% on Pulau Tello–Teluk Dalam. The maximum cargo load factor is 0.336% on Teluk Bayur–Panasahan, calculated as 4,878/(29×50,000)×100. Pulau Tello–Teluk Dalam reaches 0.095% and Teluk Dalam–Sibolga 0.080%. Panasahan–Sioban is zero for both outputs. Under the agreed interpretation of cargo data as kilograms, the vessel's 400-passenger and 50-t cargo capacities are therefore well above recorded segment demand.

3.3. Transport-demand Scenarios

Passenger traffic increased from 6,153 in 2022 to 7,230 in 2024. For 2030, the low, base, and high scenarios yield 7,230, 10,484, and 11,749 passengers, respectively as showed in Figure 2. These values indicate a plausible planning range, not a statistical prediction interval. Even the high scenario must be converted into demand per segment and sailing before it is compared with vessel capacity. Cargo fluctuated between 4,952 and 6,725 kg over the observed years; because its trend is statistically insignificant, a cargo point forecast is excluded from capacity decisions.

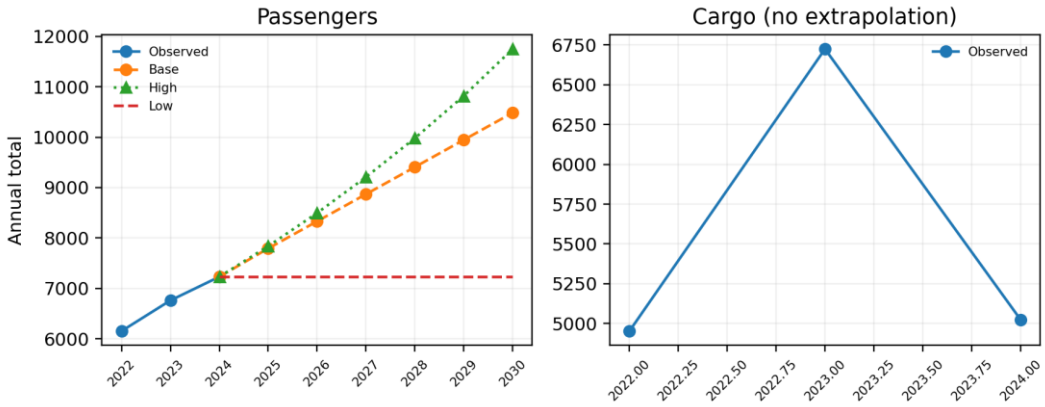


Figure 2. Observed 2022-2024 traffic and Passenger-demand scenarios for 2025-2030

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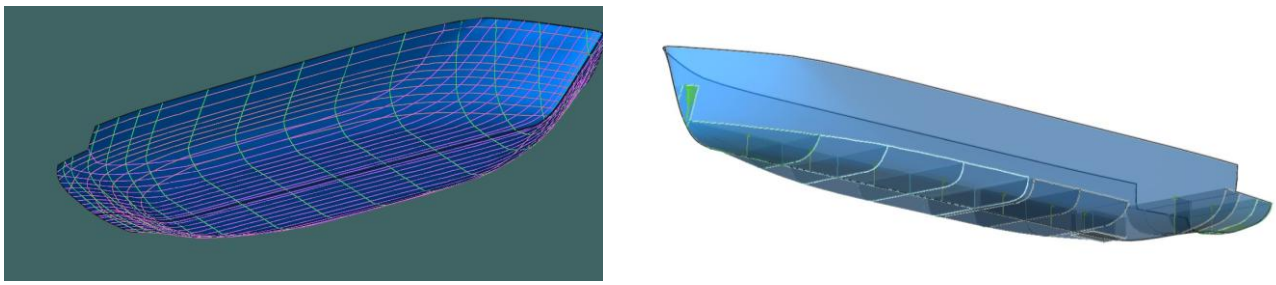


Figure 3. Hull Geometry and Compartment Arrangement Used The Simulations

Figure 3 presents the three-dimensional hull geometry and compartment arrangement used to develop the numerical model of KM Sabuk Nusantara 37. The wireframe model defines the vessel's hull form through longitudinal and transverse lines, while the compartment model represents the internal subdivision and loading spaces considered in the stability calculations. The model was subsequently used to evaluate intact stability, resistance, power requirements, and seakeeping responses under the specified loading and environmental conditions.

3.4. Resistance and Power Performance

Resistance and required power increase nonlinearly with speed. At 9 knots, the dataset gives 25.6 kN and 317.344 HP; at 12 knots, approximately 61.1–61.6 kN and 1,012–1,020 HP; and at 15 knots, 155.2 kN and 3,212.577 HP. The steep increase at higher speeds means that schedule recovery by accelerating the ship can be costly. Improving cargo handling and reducing unproductive port time may preserve the timetable at a lower transit speed, consistent with ferry port-efficiency findings as showed in Figure 4. At 12 knots the estimated requirement remains below the installed 1,500-kW main-engine rating, although a detailed propulsion-margin assessment should also include transmission losses, sea margin, fouling, auxiliaries, and engine derating.

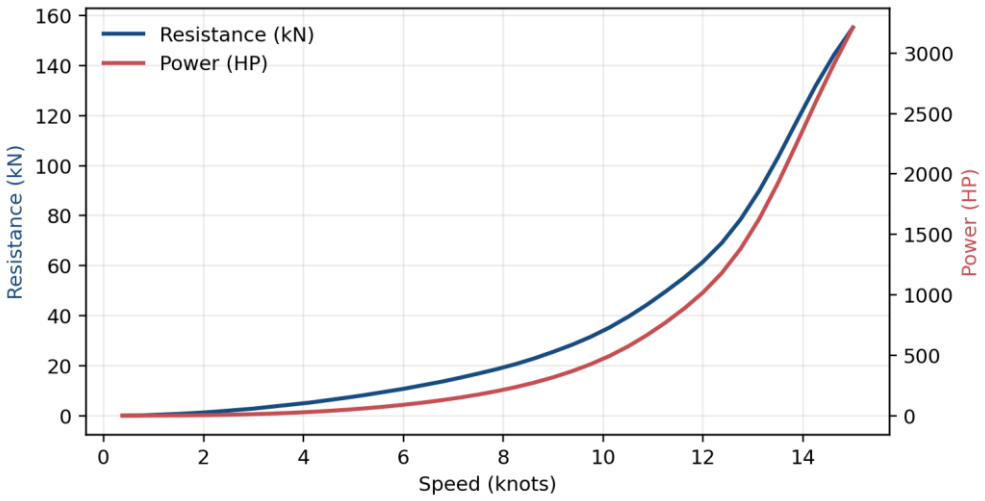


Figure 4. Speed, Resistance, and Power Requirement of KM Sabuk Nusan

3.5. Stability and Seakeeping Response

Intact stability was calculated for four departure and arrival loading conditions. The maximum case contains 400 passengers at an assumed 0.1 t per person and 50 t of cargo; the low-service case contains 30 passengers and 5 t of cargo. Displacement ranges from 833.097 to 1,300.683 t. Every case passes the adopted IMO criteria: GZ area from 0° to 30° is 32.2950–35.9072 m·deg, area from 0° to 40° is 52.4317–61.7751 m·deg, maximum GZ is 2.194–3.058 m, the maximum-GZ angle is 50.0°–53.6°, and initial GMt is 4.520–5.025 m. The model therefore provides a positive intact-stability margin for all tested loading cases.

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Table 2. Seakeeping Response in The Supplied Dataset

Parameter	Scenario A RMS	Scenario B RMS	Dataset criterion	Initial status
Heave	0,312 m	0,471 m	–	Descriptive
Roll	0,00°	0,00°	6°*	Pass
Pitch	1,24°	1,47°	3°*	Pass
Heave acceleration	0,049 m/s²	0,595 m/s²	0,2 g*	Pass

*Criteria follow the initial worksheet list; labels in the internal status table appear interchanged and require verification.

As in Table 2 the RMS pitch in both reported scenarios is below the adopted 3° limit, and RMS heave acceleration is below 0.2g (approximately 1.962 m/s²). The results support technical readiness for the simulated condition, but they cannot establish year-round route operability because only one wave height, one period, one speed, and two inconsistently labelled headings are represented. A stronger operability assessment would use seasonal wave scatter data, multiple speeds and headings, and response locations relevant to passengers and crew.

3.6. Implications for service improvement

The combined evidence shows that vessel capacity is not the binding constraint. Improvement should focus on schedule control and passenger information to close the reliability gap; maintenance of onboard and port facilities to address tangibles; coordinated cargo consolidation and local economic scheduling; and demand-responsive frequency on low-productivity segments. For pioneer-shipping management, the integrated indicators should be used as a diagnostic dashboard rather than as a single closure rule. Service-quality gaps identify what users experience, DEA identifies segments with high service-hours relative to traffic, load factors reveal spare capacity, and technical results confirm whether the assigned vessel can safely provide the service. A low DEA score is therefore not an automatic basis for removing a pioneer call because the service has a statutory social-connectivity mandate. Each low-output segment should be reviewed against access to health, education, markets, alternative modes, and the feasibility of combining sailings or cargo flows.

The 2025 pattern no longer calls at Panasahan. This adjustment is consistent with the 2024 results because Panasahan–Sioban scores zero and Panasahan–Teluk Bayur scores 0.011. Omitting an unproductive call can reduce sailing time and operating cost, but the accessibility effect on Panasahan residents must be monitored. Route optimization should therefore be formulated as a constrained public-service problem: minimize avoidable sailing and port time while preserving a defined minimum level of access for communities without reasonable alternatives. Practical options include reducing frequency rather than eliminating a call, using scheduled demand windows, coordinating cargo consolidation with local governments, and periodically reassessing traffic after the timetable change.

The findings also have implications for service subsidies and operating contracts. Subsidy allocation should not be tied exclusively to aggregate passenger or cargo volume because this would penalize socially necessary low-demand links. A more balanced contract can combine a fixed accessibility component—covering the minimum mandated network—with performance-based indicators for completed voyages, schedule reliability, data reporting, port-time control, and service-quality improvement. Segment-level DEA and load-factor results can support annual route reviews and transparent negotiations between the central government, local governments, and the operator, while the social-access assessment acts as a safeguard against purely commercial route rationalization. This approach is consistent with evidence that tender design and capacity decisions influence the cost and effectiveness of publicly supported ferry services.

4. CONCLUSION

KM Sabuk Nusantara 37 provides an important lifeline on route R-3, but service performance does not yet meet all user expectations. The overall service-quality gap is −0.4150, led by reliability and tangibles. Three segments form the CCR relative-efficiency frontier, while Panasahan–Sioban scores zero. Passenger load factors of 0–15.58% and cargo load factors of 0–0.336% show that the existing capacity of 400 passengers and 50 t remains adequate. The 2030 passenger scenarios range from 7,230 to 11,749, whereas cargo is not projected because no significant trend is present. The omission of Panasahan in the 2025 pattern is operationally consistent with the low 2024 productivity of its adjoining segments, subject to continued

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monitoring of community access. All tested loading conditions satisfy the adopted intact-stability criteria; installed engine power exceeds the estimated 12-knot requirement; and motion responses comply with the limits used in the simulation. The three research objectives consequently lead to one policy conclusion: effectiveness should be strengthened through reliable schedules, better facilities, cargo consolidation, demand-responsive frequency, and government–operator coordination, not through additional vessel capacity.

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