

Developing a Multi-Objective Maritime Vehicle Routing Framework for Integrated Passenger–Cargo Services in Small Island Networks: A Scenario-Based Assessment of the Thousand Islands, Indonesia

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ABSTRACT:

Maritime transportation plays a critical role in maintaining mobility, logistics distribution, and regional connectivity in archipelagic regions. However, small-island transportation systems frequently experience operational inefficiencies arising from fragmented passenger and cargo services, low vessel utilization, accessibility disparities, and empty sailing movements. These challenges are evident in the Thousand Islands Regency (Kepulauan Seribu), Indonesia, where government-subsidized passenger vessels operate alongside traditional passenger–cargo services, resulting in duplicated operations and uneven service accessibility. This study develops a Multi-Objective Maritime Vehicle Routing Framework (MO-MVRF) to support integrated passenger–cargo transportation planning in small island networks. Unlike conventional maritime vehicle routing approaches that primarily focus on cost minimization, the proposed framework simultaneously incorporates operational efficiency, accessibility equity, vessel utilization, and passenger–cargo service integration within a unified decision-support structure. Using operational data from January–December 2024, including vessel movements, passenger demand, cargo service records, and inter-island distance matrices, the study evaluates existing network performance through three indicators: the Empty Sailing Index (ESI), Island Accessibility Deficit Index (IADI), and Cargo Accessibility Index (CAI). The analysis identified 328 empty departure trips and 530 empty arrival trips, representing 8.88% and 13.86% of annual vessel movements, respectively. Significant accessibility disparities were also observed, with Harapan and Sabira Islands experiencing service absence during 64.7% and 56.2% of operational days, respectively, while cargo services remained concentrated on a limited number of islands. A scenario-based evaluation was subsequently conducted to compare the existing fragmented transportation arrangement with the proposed integrated routing concept. The results indicate that the proposed framework can support demand consolidation, reduce empty sailing occurrences, improve vessel utilization, and enhance accessibility for peripheral islands through feeder-based service integration. The study contributes to the maritime transportation literature by extending multi-objective vehicle routing concepts to

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integrated passenger–cargo services in small island environments and provides a transferable framework for policymakers and transport operators seeking more efficient, equitable, and sustainable maritime transportation systems in archipelagic regions.

Keywords: Multi-Objective Maritime Vehicle Routing; Passenger–Cargo Integration; Small Island Transportation; Maritime Accessibility; Empty Sailing; Archipelagic Transport Planning.

1. Introduction

Maritime transportation plays a fundamental role in supporting economic development, social interaction, and regional integration in archipelagic regions by facilitating the movement of people, goods, and services across geographically separated areas. Unlike continental regions that rely primarily on road and rail networks, island communities depend heavily on maritime transportation to maintain connectivity with economic centers, access public services, and support local economic activities. Consequently, the performance of maritime transportation systems significantly influences regional accessibility, logistics efficiency, and socioeconomic development (Banerjee et al., 2020; Fratila et al., 2021).

Indonesia, as the world's largest archipelagic nation, faces significant challenges in providing efficient and equitable transportation services across its dispersed islands. Maritime transportation serves as a critical component of national connectivity, supporting passenger mobility, freight distribution, tourism activities, and regional economic integration (Gani, 2017; Fitriani & Imtiyaz, 2023). However, many island transportation systems continue to experience operational inefficiencies due to low demand density, uneven service distribution, and high operating costs, particularly in remote and small-island environments (Collins & Diansari, 2018; Humang et al., 2023).

The Thousand Islands Regency (Kepulauan Seribu), located in Jakarta Bay, represents a unique case of maritime dependency despite its proximity to Indonesia's capital city. The region

consists of numerous inhabited islands whose residents rely almost entirely on maritime transportation for passenger mobility, freight distribution, tourism activities, and access to essential services. The existing transportation system is characterized by the coexistence of government-subsidized passenger vessels and traditional commercial vessels that transport both passengers and cargo. While this arrangement improves passenger accessibility, it also creates inefficiencies through duplicated services, low vessel utilization, and fragmented transportation operations.

Operational records from 2024 reveal substantial inefficiencies within the existing maritime network. A total of 328 empty departure trips and 530 empty arrival trips were recorded, representing 8.88% and 13.86% of annual vessel movements, respectively. Significant accessibility disparities were also identified among islands. Harapan Island experienced service absence during 64.7% of operational days, while Sabira Island experienced service absence during 56.2% of operational days. Cargo services were concentrated on a limited number of islands, leaving peripheral islands dependent on indirect feeder arrangements. These findings indicate that the current transportation system remains fragmented and demand-oriented, resulting in unequal accessibility and inefficient utilization of maritime resources.

Recent studies have demonstrated the potential of maritime vehicle routing and integrated passenger–cargo transportation strategies for improving operational efficiency and accessibility in island transportation systems (Psaraftis, 2019; Wang & Yang, 2024; Humang et al., 2023).

Nevertheless, existing studies generally examine maritime accessibility, logistics performance, or routing optimization separately. Limited attention has been given to the simultaneous consideration of operational efficiency, accessibility equity, vessel utilization, and passenger–cargo integration within a unified framework for small island transportation networks. As a result, transportation planning in archipelagic regions often lacks a comprehensive decision-support framework capable of balancing both efficiency and accessibility objectives.

A Multi-Objective Maritime Vehicle Routing Framework (MO-MVRF) is developed in this study to support integrated passenger–cargo transportation planning in small island networks. The proposed framework differs from conventional maritime routing approaches by incorporating four planning dimensions, namely operational efficiency, accessibility equity, vessel utilization, and passenger–cargo service integration. Three performance indicators are also introduced to support framework evaluation: the Empty Sailing Index (ESI), Island Accessibility Deficit Index (IADI), and Cargo Accessibility Index (CAI). These indicators provide a practical basis for identifying service deficiencies and assessing transportation performance in island transportation systems.

The study pursues three objectives. The first is to evaluate the operational performance of the existing maritime transportation network in the Thousand Islands. The second is to identify inefficiencies associated with empty sailings, accessibility disparities, and fragmented passenger–cargo services. The third is to develop and evaluate a multi-objective routing framework that supports integrated passenger–cargo operations through a scenario-based assessment approach. The findings contribute to the growing literature on maritime transportation planning and provide practical guidance for policymakers and transportation operators seeking more efficient, equitable, and sustainable transportation systems in archipelagic regions.

2. Methodology

2.1 Study Area and Data Collection

The study was conducted in the Thousand Islands Regency (Kepulauan Seribu), Jakarta, Indonesia, which consists of inhabited islands connected to mainland ports through maritime transportation services. The analysis focused on major passenger and cargo destinations, including Pari, Pramuka, Tidung, Harapan, Kelapa, and Sabira Islands.

Secondary data were collected from the Jakarta Transportation Agency and operational records for the period January–December 2024. The dataset included vessel departure and arrival records, passenger transportation services, cargo transportation services, and route information between islands and mainland ports. Data preprocessing involved removing duplicate records, checking route consistency, and aggregating vessel movements by destination island and service type.

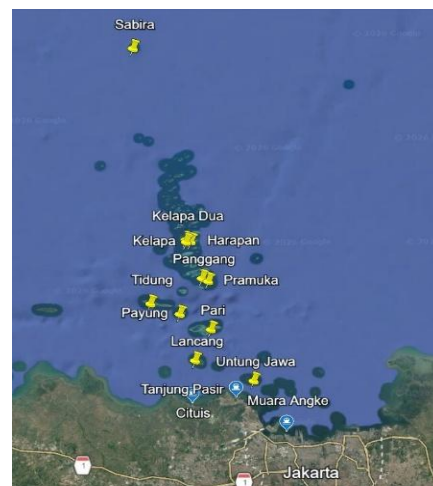


Figure 1 Study Area of the Thousand Islands Transportation Network

Inter-island distances were calculated using the Haversine formula:

$$d_{ij} = 2R \times \arcsin \left\{ \sqrt{ \left[\sin^2((\varphi_j - \varphi_i)/2) + \cos(\varphi_i) \times \cos(\varphi_j) \times \sin^2((\lambda_j - \lambda_i)/2) \right] } \right\} \quad (1)$$

where d_{ij} is the distance between locations i and j , R is the Earth's radius, φ denotes latitude, and λ denotes longitude.

2.2 Operational Performance Assessment

Three indicators were developed to evaluate transportation performance and support framework validation.

Empty Sailing Index (ESI)

$$ESI = N_e / N_t \quad (2)$$

where N_e is the number of empty vessel trips and N_t is the total number of vessel trips.

Island Accessibility Deficit Index (IADI)

$$IADI_i = D_i / 365 \quad (3)$$

where D_i represents the number of days without transportation services for island i .

Cargo Accessibility Index (CAI)

$$CAI_i = F_i / F_{\max} \quad (4)$$

where F_i denotes the cargo service frequency serving island i and $F_{\max}$ represents the highest cargo service frequency observed among all islands.

Higher ESI and IADI values indicate lower transportation performance, while higher CAI values indicate better cargo accessibility.

2.3 Multi-Objective Maritime Vehicle Routing Framework

The transportation network is represented as a graph $G = (N, A)$, where N denotes the set of ports and islands and A represents maritime links connecting the nodes.

The routing decision variable is defined as:

$$\begin{aligned} x_{ijk} &= 1, \text{ if vessel } k \text{ travels from node } i \text{ to node } j \\ x_{ijk} &= 0, \text{ otherwise} \end{aligned} \quad (5)$$

The proposed framework simultaneously considers operational efficiency, accessibility, and transportation demand through the following objective function:

$$\text{Min } Z = w_1 \sum \sum \sum c_{ij} x_{ijk} + w_2 E + w_3 U \quad (6)$$

where c_{ij} is the transportation cost between nodes i and j , E is the number of empty sailing trips, U represents unmet passenger and cargo demand, and w_1 , w_2 , and w_3 are weighting parameters.

Equal weights were assumed in this study because the framework focuses on conceptual development and scenario evaluation rather than full-scale optimization. Future studies may determine weights using Multi-Criteria Decision Analysis (MCDA) or Analytic Hierarchy Process (AHP).

The framework is subject to the following constraints:

Service Coverage Constraint:

$$\sum \sum x_{ijk} \geq 1 \quad (7)$$

Route Continuity Constraint:

$$\sum x_{ijk} = \sum x_{jlk} \quad (8)$$

Passenger Capacity Constraint:

$$P_{jk} \leq C_k^p \quad (9)$$

Cargo Capacity Constraint:

$$Q_{jk} \leq CQ_k \quad (10)$$

Maximum Sailing Time Constraint:

$$\sum \sum t_{ij} x_{ijk} \leq T_k \quad (11)$$

where P_{jk} and Q_{jk} represent passenger and cargo loads, C_k^p and CQ_k denote vessel capacities, t_{ij} is travel time, and T_k is the maximum allowable operating time.

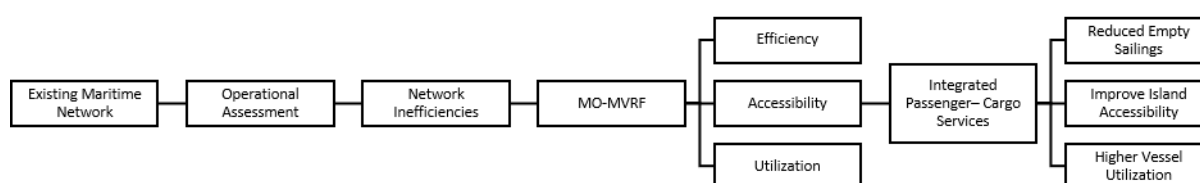


Figure 2 Conceptual Structure of the Proposed MO-MVRF

2.4 Scenario-Based Framework Evaluation

The practical applicability of the proposed framework was examined through a scenario-based evaluation. The existing transportation arrangement, characterized by separate passenger and cargo operations, was compared with an integrated passenger–cargo routing concept. Framework validation was performed using comparative operational indicators, including ESI, IADI, and CAI. The evaluation focused on the potential for reducing empty sailings, improving accessibility, and enhancing vessel utilization within the transportation network.

3. Results and Discussion

3.1 Existing Maritime Network Performance

The operational performance of maritime transportation services in the Thousand Islands was evaluated using vessel movement records during 2024. The analysis identified substantial inefficiencies within the existing transportation system, particularly in relation to empty vessel movements. During the study period, a total of 3,693 vessel departures and 3,824 vessel arrivals were recorded. Among these movements, 328 departure trips and 530 arrival trips occurred without carrying passengers or cargo.

Table 1 summarizes the operational performance indicators of the existing network.

Table 1 Existing Maritime Network Performance Indicators

Indicator	Value
Total vessel departures	3,693
Empty departures	328
Empty Departure Ratio	8.88%
Total vessel arrivals	3,824
Empty arrivals	530
Empty Arrival Ratio	13.86%

The results indicate that arrival inefficiencies were substantially higher than departure inefficiencies. This pattern suggests that vessels frequently returned to mainland ports or repositioned themselves without generating revenue from passenger or cargo services. Such

conditions reduce vessel utilization, increase fuel consumption, and contribute to unnecessary operating costs. The findings also demonstrate the operational consequences of maintaining parallel passenger and freight transportation systems in which government-operated vessels primarily serve passenger demand while traditional vessels continue to provide freight services.

3.2 Accessibility Inequality Among Islands

Accessibility performance was assessed using the Island Accessibility Deficit Index (IADI), which measures the proportion of days during which an island did not receive transportation services.

Table 2 summarizes the accessibility conditions of major inhabited islands.

Table 2 Accessibility Deficit of Major Islands

Island	Days Without Service	IADI
Pari	22	0.060
Pramuka	4	0.011
Tidung	7	0.019
Harapan	236	0.647
Kelapa	3	0.008
Sabira	205	0.562

Substantial accessibility disparities were observed across the network. Pramuka, Kelapa, and Tidung maintained relatively high service availability throughout the year, whereas Harapan and Sabira experienced severe accessibility deficits. Harapan Island lacked direct services during approximately 64.7% of operational days, while Sabira experienced service absence during 56.2% of operational days.

These findings suggest that transportation services are concentrated on high-demand corridors, resulting in unequal accessibility conditions among island communities. Similar accessibility challenges have been reported in other island transportation systems where service allocation is strongly influenced by demand concentration and operational profitability (Agius et al., 2021). Consequently, accessibility-based planning approaches are required to complement

conventional demand-driven transportation strategies.

3.3 Cargo Service Distribution and Network Connectivity

Cargo transportation services remain largely dependent on traditional vessels. During 2024, a total of 166 cargo service departures were recorded across the transportation network.

Table 3 Cargo Service Distribution and Cargo Accessibility Index

Island	Cargo Services	CAI
Pari	37	0.62
Pramuka	60	1.00
Tidung	31	0.52
Harapan	5	0.08
Kelapa	33	0.55
Sabira	0	0.00

Pramuka Island recorded the highest cargo service frequency and served as one of the primary logistics destinations within the network. In contrast, Harapan received only five cargo services throughout the year, while Sabira received no direct regular cargo services.

The absence of direct cargo services to Sabira indicates a strong dependence on indirect feeder-based distribution arrangements. Although such arrangements may reduce operating costs for service providers, they increase delivery complexity and potentially reduce logistics reliability. These findings are consistent with previous studies highlighting the vulnerability of peripheral island communities to transportation and logistics constraints (Humang et al., 2023; Collins & Diansari, 2018).

3.4 Comparative Discussion with Previous Studies

The observed transportation inefficiencies are consistent with previous findings in island transportation systems where fragmented services often generate duplicated operations, underutilized assets, and accessibility inequalities (Myriouni et al., 2025). Similar challenges have also been reported in Mediterranean island transportation networks, where maintaining

accessibility and operational sustainability simultaneously remains a significant policy challenge (Agius et al., 2021).

Compared with conventional maritime routing studies that primarily emphasize cost minimization (Psaraftis, 2019), the present study explicitly incorporates accessibility and passenger–cargo integration as planning objectives. This distinction is particularly important for small island environments where transportation services fulfill both economic and social functions. Furthermore, the use of ESI, IADI, and CAI provides a practical set of indicators for evaluating transportation performance beyond traditional operational metrics.

3.5 Scenario-Based Evaluation of the Proposed MO-MVRF

To demonstrate the practical applicability of the proposed framework, a scenario-based evaluation was conducted by comparing the existing transportation arrangement with an integrated passenger–cargo routing concept.

Under the existing system, passenger and freight services are partially separated, resulting in duplicated operations and relatively high levels of empty vessel movements. In contrast, the proposed MO-MVRF consolidates passenger and cargo demand within a unified transportation structure while introducing feeder services for remote islands.

The proposed framework identifies Pramuka, Kelapa, and Tidung as potential service hubs due to their relatively high transportation activity and cargo accessibility levels. Meanwhile, Harapan and Sabira are proposed to be connected through feeder services that improve service continuity and reduce accessibility deficits.

Although detailed optimization was beyond the scope of the available dataset, the comparative assessment indicates that integrated passenger–cargo services have the potential to reduce empty sailings, improve vessel utilization, and enhance accessibility for peripheral islands. The framework therefore provides a practical decision-support tool for transportation planners

seeking to balance operational efficiency and accessibility objectives.

3. 6 Policy Implications and Sustainability Considerations

The findings highlight the importance of transitioning from fragmented transportation operations toward integrated passenger–cargo transportation planning. From a policy perspective, coordination between government-operated passenger services and traditional vessel operators is essential to improve network efficiency and reduce redundant services.

The proposed framework also supports sustainability objectives by reducing empty sailing occurrences and improving vessel utilization. Although detailed fuel consumption and emission data were unavailable, previous studies have demonstrated that improvements in transportation efficiency are directly associated with reductions in fuel use and greenhouse gas emissions (Wang & Yang, 2024). Therefore, the proposed MO-MVRF offers not only operational benefits but also potential environmental advantages for archipelagic transportation systems.

4. Conclusion

This study developed a Multi-Objective Maritime Vehicle Routing Framework (MO-MVRF) to support integrated passenger–cargo transportation planning in small island networks, using the Thousand Islands Regency, Indonesia, as a case study. The analysis of operational data from 2024 revealed several inefficiencies within the existing maritime transportation system. A total of 328 empty departure trips and 530 empty arrival trips were identified, corresponding to Empty Sailing Index values of 8.88% and 13.86%, respectively. Furthermore, substantial accessibility disparities were observed among islands, with Harapan and Sabira experiencing service absence during 64.7% and 56.2% of operational days. Cargo services were also concentrated on a limited number of islands, leaving peripheral communities dependent on indirect feeder arrangements.

The findings indicate that the existing transportation network remains fragmented, with government-operated passenger services and traditional passenger–cargo services functioning as parallel systems rather than as an integrated network. This operational structure contributes to duplicated services, low vessel utilization, accessibility inequalities, and inefficient allocation of transportation resources. To address these challenges, the proposed MO-MVRF integrates passenger and cargo demand within a unified transportation framework while simultaneously considering operational efficiency, accessibility equity, and vessel utilization objectives. The framework further introduces the Empty Sailing Index (ESI), Island Accessibility Deficit Index (IADI), and Cargo Accessibility Index (CAI) as practical indicators for evaluating transportation performance in small island environments.

A scenario-based evaluation demonstrated that the proposed framework has the potential to improve service integration through demand consolidation and feeder-based connectivity strategies. The identification of Pramuka, Kelapa, and Tidung as potential service hubs, together with feeder connections to Harapan and Sabira, provides a practical direction for improving network accessibility while reducing operational inefficiencies. Although quantitative optimization was beyond the scope of the available dataset, the framework establishes a foundation for future transportation planning and decision-making in archipelagic regions.

From a policy perspective, the findings highlight the importance of stronger coordination between public transportation authorities and traditional vessel operators. Integrated route planning, accessibility-based service allocation, and the development of feeder services for remote islands may improve both transportation efficiency and social equity. In addition, reducing empty sailing movements can contribute to lower fuel consumption and support broader sustainability objectives in maritime transportation systems.

Several limitations should be acknowledged. The study relied primarily on operational service

records and did not include detailed vessel characteristics, operational costs, fuel consumption data, or origin–destination demand matrices. Consequently, the framework was evaluated using comparative performance indicators and scenario-based assessment rather than full-scale optimization modelling. Future research should incorporate detailed operational datasets to enable the application of optimization algorithms such as Mixed Integer Linear Programming (MILP), Genetic Algorithms (GA), and other metaheuristic approaches. Further

studies may also perform sensitivity analyses and simulation experiments to quantify potential reductions in operating costs, emissions, and unmet transportation demand under alternative routing scenarios. Despite these limitations, the proposed MO-MVRF provides a transferable decision-support framework that can assist policymakers and transportation operators in developing more efficient, equitable, and sustainable maritime transportation systems in archipelagic regions.

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