JOURNAL OF MARITIME RESEARCH

Vol XXIII. No. II (2026) pp 306–312

ISSN: 1697-4840, **www.jmr.unican.es**

Enhancing Low-Demand Island Shipping: A Network Model with Investment Cost Considerations

Adrian Firdaus[1,2,*], Ade Sjafruddin[1], Russ Bona Frazila[1], Febri Zukhruf[1]

ARTICLE INFO

Article history:
Received XXXXXX;
in revised form XXXXXX;
accepted XXXXXX.

Keywords:
Low-Demand, Island, Network, Investment.

ABSTRACT

Remote islands face significant challenges due to their low demand volumes that render shipping commercially unviable. As shipments primarily consist of essential goods for residents, governments are often required to manage the service. This paper develops a network model to improve shipping in low-demand island regions within a hub–spoke–feeder framework, explicitly incorporating investment costs, an aspect rarely addressed in the literature. Investment cost is a critical factor, as limited budgets necessitate careful selection of feeder ports to be upgraded into spokes. Optimal spoke locations are identified by maximizing the benefit–cost ratio (BCR), defined as the reduction in shipping costs relative to the do-nothing baseline divided by the investment required. The proposed model then applied on an actual case study in eastern Indonesia. The numerical results show that a 2-spoke scheme, where two spoke nodes operate simultaneously, yields the highest BCR. The resulting value exceeds one, indicating that investment in port upgrades is economically justified. Moreover, the 2-spoke scheme enhances network resilience, as one spoke can temporarily serve as a backup if the other is disrupted, ensuring the reliable delivery of essential goods to island communities.

1. Introduction.

An island group, also referred to as an archipelago, is a chain or cluster of islands that may be classified as oceanic islands, continental fragments, or continental islands, depending on their geological and geographical characteristics. Island Groups can be found either isolated in vast oceanic waters or situated in proximity to major landmasses (Whittaker & Fernandez-Palacios, 2007). Owing to their geographical nature, island groups are highly reliant on maritime shipping to sustain economic development, ensure inter-island connectivity, and enable the efficient distribution of essential goods and services. Maritime transport serves as a vital lifeline for these regions, supporting trade flows, linking remote communities to broader markets and opportunities, and fostering national economic integration by reducing logistical costs and enhancing supply chain efficiency (Amin et al., 2021).

In many island regions, the primary challenge of maritime transport lies in the limited hinterland of each port, which results in low cargo volumes and the absence of backhaul flows (Shareef et al., 2019; Achmadi et al., 2021; Amin et al., 2021). Such conditions make shipping operations financially unviable, as transportation costs cannot be offset by the available cargo demand. Consequently, the responsibility for sustaining inter-island shipping often falls to the government. In this context, the government is required to develop port infrastructure and design shipment patterns that can accommodate the distribution of goods, predominantly essential commodities, across the islands within the group. Given the typically constrained nature of public budgets, careful allocation of investment becomes imperative to ensure the continuity and efficiency of island shipping services.

To improve shipping efficiency in low-demand island groups,

[1]Faculty of Civil and Environmental Engineering, Institut Teknologi Bandung, Bandung, 40132, Indonesia.

[2]Department of Civil Engineering, Universitas Katolik Parahyangan, Bandung, 40141, Indonesia.

[*]Corresponding author: Adrian Firdaus. E-mail Address: adrianfirdaus@unpar.ac.id.

a hub-and-spoke framework can be applied to minimize transport costs while accounting for investment requirements. In this framework, hub nodes serve large hinterlands and handle greater volumes through superior facilities, while spokes are smaller ports with limited demand (Zhou et al., 2023; Humang et al., 2025; Saha & Khalil, 2025). To extend accessibility, a third tier—the feeder—is often added, functioning as the final origin or destination. Unlike earlier models that linked feeders directly to hubs (Kuby & Gray, 1993; Guo et al., 2023), more recent studies (e.g., Wang et al., 2023; Firdaus et al., 2024) represent all three node types within a closed-loop structure. Larger vessels deployed on hub–spoke routes lower unit transport costs compared to spoke–feeder routes, with this cost differential commonly represented by a discount factor (Wei et al., 2017; Dukkanci et al., 2019; Ghaffarinasab et al., 2023). However, most of these studies give limited attention to demand volumes, and even fewer focus specifically on the challenges of sustaining networks in low-demand contexts.

Research on demand shipping has largely concentrated on demand fluctuations in maritime transport, rather than on enduring conditions of limited demand, which is commonly found in islands region. Merkel et al. (2020) examined demand elasticity in short-sea shipping, while Crotti et al. (2022) and Park et al. (2023) analyzed demand shocks in container and dry bulk shipping, respectively. Kisialiou et al. (2019) and Song (2021) explored demand uncertainty and its implications for shipping operations. While these contributions are valuable, they largely emphasize variability and shifting demand patterns, rather than situations where low demand makes government intervention essential due to the limited financial feasibility for private operators. Addressing this gap, the implementation of a hub–spoke–feeder network that incorporates investment costs offers a potential solution, as the inclusion of feeders is critical for extending the connectivity across island regions. Yet, most hub-and-spoke studies devote little attention to investment costs, which are crucial for guiding the optimal allocation of scarce government budgets in enhancing low-demand shipping.

This study aims to present an approach to improving shipping in low-demand island regions by applying a hub-and-spoke network model that explicitly incorporates investment costs into network performance evaluation. The model includes feeder nodes as a third tier beneath hub and spoke nodes. Due to the low-demand issue, the model is designed from a governmental perspective, in which the objective is to identify the most optimal spoke location by maximizing the benefit–cost ratio (BCR) of the implemented network. In this formulation, benefits are represented by the reduction in total shipping costs compared to the existing conditions, while costs refer to the required investment expenditures. A real-world archipelago in Eastern Indonesia is used as the case study, where small island ports function as feeders and medium-sized ports serve as spokes. The model considers only inbound (hub – spoke – feeder) flows, reflecting the common imbalance in which outbound (feeder – spoke – hub) flows (backhaul) are negligible and strategic decisions are therefore driven predominantly by inbound logistics.

2. Network Model Considering Investment Cost.

2.1. Network Topology.

We adopt and extend the three-tier hub-and-spoke framework of Wang et al. (2023) and Firdaus et al. (2024), to consider the investment cost needed to upgrade the selected feeder into spoke node. In this architecture (refer to Fig. 1), the link between hub and spoke carry containerized cargo on container vessels; and link between spoke and feeder carry break-bulk cargo on general-cargo ships.

At each spoke, a de-containerization process converts break-bulk shipments into containerized loads (and vice versa). This structure captures the hierarchical maritime logistics typical of island regions and provides the foundation for the BCR - maximization model developed hereinafter. The model seeks to (i) determine both the optimal number and location of spoke ports, selected from a set of candidate feeders, and (ii) assign each feeder to one of those spokes. The model takes government's point of view, so that decision criterion is based on the maximization of BCR value of the implemented network.

2.2. Notation.

The mathematical symbols are summarized in Table 1, in which the formulation relies on three key assumptions:

- Single-vessel service: Each link is operated by exactly one vessel with assumed constant speed
- Immediate de-containerization: Cargo bound for a feeder port is de-containerized upon arrival at its spoke, so no consolidation-waiting time across feeders is considered.
- Fixed hubs: The locations of hub nodes are given.

2.3. Cost Function.

The objective of the model is shown in Equation (1), which is to maximize the benefit - cost ratio (BCR) of the implemented network. The benefit, which is the numerator of Equation (1), is represented by the gap between the cost of existing condition (C^{dnot}) and the cost generated from the implemented model. The cost generated by the implemented model is the sum of link-related transport cost (C^{link}) and node-handling costs (C^{node}). The cost part of the BCR is the denominator of Equation (1), which is the investment cost (C^{link}) required to upgrade a feeder port to spoke status. A binary decision variable h_i governs each upgrade decision, taking the value 1 when feeder i is converted into a spoke and 0 when the feeder remains unchanged; the BCR maximization problem is therefore expressed compactly in Equation (1).

The cost of existing conditions, or the do - nothing cost (C^{dnot}), depends on the existing network topology of the island group. If the network is implemented to the greenfield network (refer to the Existing Condition in Figure 1), where the shipment is conducted directly from hub to feeder, C^{dnot}can be calculated by adding C^{link} and C^{node}, with h_i equal to 0. Note that the demand flow used to calculate both conditions (existing and implemented) must be the same.

The formulation is governed by several constraints.

Table 1: Mathematical Notation.

Notations	Description
Indices	
i	Feeder ports
j	Spoke Ports
k	Hub Nodes
N	Set of nodes, $i, j, k \in N$
l	Commodities, l = (1) for general cargo; and l = (2) for container
Parameters	
C^{dnot}	Total cost of existing condition (do-nothing cost)
C^{link}	Link-related transport cost
C^{node}	Node-handling costs
C^{invs}	Investment cost
$d_{kj}; d_{ji}$	Distance between: hub and spoke nodes; spoke and feeder nodes
$w_{kj}; w_{ji}; w_{ki}$	Demand flow (TEUs) between: hub and spoke nodes; spoke and feeder nodes; hub and feeder nodes
c^l	Transportation tariff, for l = (1) cargo ship (per ton Nautical Miles (NM)); and (2) container ship (per TEUs NM)
v^l	Average ship speed (NM per hour), for l = (1) cargo ship; and (2) container ship
m^l	Ship Capacity, for l = (1) cargo ship (ton); and (2) container ship (TEUs)
g^l	Ship Weight (Gross Tonnage (GT)), for l = (1) cargo ship; and (2) container ship
f	Capacity of a container (ton per TEUs)
$s_i^l; s_j^l; s_k^l$	Ship to Berth loading/unloading productivity, for l = (1) general cargo (ton/hours) in feeder i or spoke j; and (2) container (TEUs/hours) in hub k or spoke j
s_j^{cfst}	De-containerization handling productivity (TEUs/hours) in spoke j
$s_k^{tran}; s_j^{tran}$	Container Transfer (Berth to Yard) productivity (TEUs/hours) in hub k or spoke j
p^l	Time cost, for l = (1) general cargo (USD per day per ton); and (2) container (USD per day per TEUs)
$t_j^{stor} t_k^{stor}$	Container Storage Duration (TEUs per day) in hub k or spoke j
x^{anch}	Anchorage Tariff (USD per ship weight per ship call)
x^{bert}	Berth Tariff (USD per ship's GT per *etmal*)
x^l	Ship to Berth Loading/Unloading Tariff, for l = (1) cargo (USD per ton); (2) container (USD per TEUs)
x^{stor}	Container Storage Tariff (USD per TEUs per day)
x^{cfst}	Container Stripping/Stuffing Tariff (USD per TEUs)
x^{tran}	Container Transfer (Berth to Yard) Tariff (USD per TEUs)
Variable	
h_i	Binary variables: 1 if feeder i is selected as spoke port, 0 if remains as feeder

Source: Author, adapted from Firdaus et al. (2024).

- All demand must be transported from hub – spoke – feeder
- Hubs may connect only to spokes; direct hub–feeder links are disallowed.
- Every feeder is linked to a chosen spoke via Dijkstra's shortest-path algorithm, yielding hub k – spoke j – feeder i path
- Demand is routed under an all-or-nothing rule: the total flow sent from a hub equals the aggregate demand of its associated feeders, so (w_{ki}=w_{kj}=w_{ji}).
- Spokes connect solely to their designated hub and feeders and spoke–spoke links are prohibited.

Link cost encompasses both transportation expense and the time-value depreciation of cargo in transit. It follows the formulation of Firdaus et al. (2024), which distinguishes container-ship services on hub–spoke legs from general-cargo services on spoke–feeder legs, as shown in Equation (2).

Each demand flow is originally defined between hub k and feeder i as w_{ki}. When a feeder is upgraded to spoke status (indicated by the binary variable h_i), that flow is split into a hub–spoke component w_{kj} and a spoke–feeder component w_{ji}. Both components are assigned using the classical all-or-nothing rule (Campbell, 1950), meaning the entire shipment travels along a single least-cost route. The least-cost hub–spoke–feeder path is identified with Dijkstra's algorithm (Dijkstra, 1959), which selects the sequence of links that minimizes total link cost. This procedure simultaneously (i) determines which feeders i are attached to each selected spoke j and (ii) aggregates the demands of all attached feeders into the flow dispatched from hub k to spoke j.

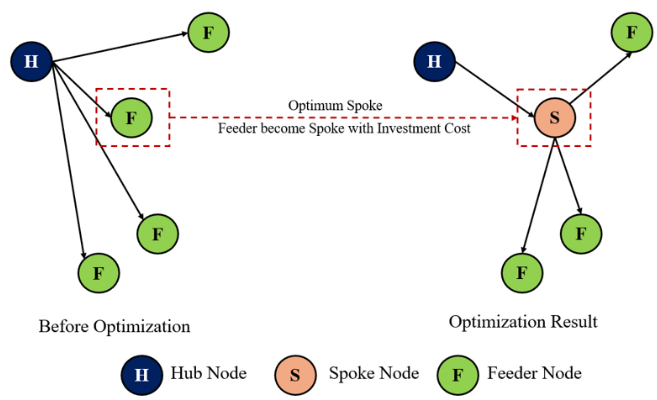
$$\max z = \frac{C^{dnot} - \left[C^{link}(h_i) + C^{node}(h_i)\right]}{C^{invs}(h_i)} \tag{1}$$

$$\begin{aligned} C^{link}(h_i) = &\sum_{i,j,k \in I,J,K} w_{kj} \left\{ \left(d_{kj} c^{(2)}\right) + \left(\frac{p^{(2)} d_{kj}}{24 v^{(2)} w_{kj}}\right) \right\} \\ &+ \sum_{i,j \in I,J} w_{ji} (1 - h_i) \left\{ \left(d_{ji} c^{(1)}\right) + \left(\frac{p^{(1)} d_{ji}}{24 v^{(1)} w_{ji}}\right) \right\} \end{aligned} \tag{2}$$

$$C^{node}(h_i) = \Bigg[\sum_{j,k\in J,K} w_{kj} \Bigg\{ \left(\frac{g^{(2)}}{m^{(2)}} x^{anch}\right) + \left(\frac{g^{(2)}}{m^{(2)}} \frac{w_{kj}}{24 s_k^{(2)}} x^{bert}\right) + \left(t_k^{stor} x^{stor}\right) + x^{tran} + x^{(2)} + \left(p^{(2)} t_k^{stor}\right) + \frac{p^{(2)}}{24 s_k^{tran}} + \frac{p^{(2)}}{24 s_k^{(2)}} + \left(\frac{g^{(2)}}{m^{(2)}} x^{anch}\right) + \left(\frac{g^{(2)}}{m^{(2)}} \frac{w_{kj}}{24 s_j^{(2)}} x^{bert}\right) + x^{(2)} + x^{tran} + \left(t_j^{stor} x^{stor}\right) + x^{cfst} + \frac{p^{(2)}}{24 s_j^{(2)}} + \frac{p^{(2)}}{24 s_j^{tran}} + \left(p^{(2)} t_j^{stor}\right) + \frac{p^{(2)}}{24 s_j^{cfst}} \Bigg\} + \sum_{i,j\in I,J} w_{ji}(1-h_i) \Bigg\{ x^{tran} + f x^{(1)} + \frac{p^{(1)}}{24 s_j^{tran}} + \frac{f p^{(1)}}{24 s_j^{(1)}} + \left(\frac{f g^{(1)}}{m^{(1)}} x^{anch}\right) + \left(\frac{f g^{(1)}}{m^{(1)}} \frac{f w_{ji}}{24 s_i^{(1)}} x^{bert}\right) + \left(f x^{(1)} + \frac{f p^{(1)}}{24 s_i^{(1)}}\right) \Bigg\} \Bigg] \quad (3)$$

$$C^{invs}(h_i) = \sum_{i\in I} h_i b_i \quad (4)$$

Figure 1: Network model considering investment cost.



Source: Authors.

The node cost (C^{node}) captures every cargo-handling and dwell-time activity at hubs, spokes, and feeders, together with the implicit cost of the time cargo spends in port. The complete formula appears in Equation (3). The investment cost (C^{invs}) is evaluated with Equation (4), where b_i denotes the investment required to upgrade feeder port i so that it can handle containers and accommodate a small-size container vessel. The upgrade budget covers the jetty extension, dredging, container yard, and essential cargo-handling equipment.

3. Case Study.

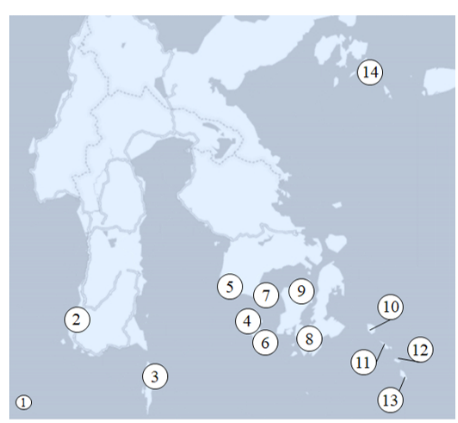
3.1. Data Sets.

This study draws on the existing island - shipping network of Eastern Indonesia as its case study (see Figure 2), while the other model input such as the demand, distance, and tariff assumptions can be found in the Appendix. The system comprises 14 ports (set N): two hubs —Tanjung Perak (Node 1) and Makassar (Node 2); one spoke— Baubau (Node 8); and 11 feeder ports, whose characteristics are based on Baubau's 2022 operational data published by the Indonesian Ministry of Transportation. The model focuses exclusively on inbound flows, which are much larger than outbound volumes and therefore drive port-development decisions. Cargo travels in containers from each hub to the spoke, is de-containerized at Baubau (node 8), and is then carried as general cargo to the feeders. For brevity, each port will be referenced by its node number, for example, Tanjung Perak is referred as Node 1.

In the existing condition, Node 1 and Node 2 serve as the hub nodes k, Node 8 serve as the spoke nodes j, while all other ports are treated as feeder nodes i. The optimization procedure then identifies which feeder(s) should be upgraded to spoke status and assigns the remaining feeders accordingly. The model permits several spokes to operate simultaneously: containerized cargo departs the hub on container vessels, is de-containerized at the selected spoke(s), and is subsequently forwarded to the feeder ports as break-bulk on general-cargo ships.

Another essential model input is the investment cost C^{invst} needed to upgrade a candidate feeder so that it can handle container vessels and related operations. The upgrades cover four components—jetty construction, dredging, container yard development, and cargo-handling equipment. Table 2 lists the corresponding costs for each feeder port, drawn from Decree No. 78/2014 of the Indonesian Ministry of Transportation, which specifies standard cost items for the sector. These figures have been converted to annualized values (capital plus operating expenditure) to align with the model's yearly time frame. The annualization assumes service lives of 20 years for the jetty, dredging works, and container yard, and 5 years for equipment. Operating costs are estimated at 20 percent of capital outlays for infrastructure and 50 percent for equipment.

Figure 2: Network for The Case Study in Eastern Indonesia.



Node	Port Name (Port of)
1	Tanjung Perak
2	Makssar
3	Selayar
4	Sikeli
5	Boepinang
6	Talaga
7	Kasipute
8	Baubau
9	Raha
10	Wanci
11	Kaledupa
12	Tomia
13	Binongko
14	Banggai

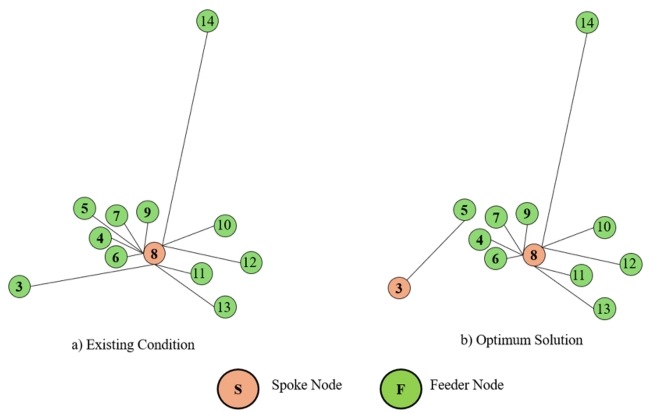
Source: Author, Modified from Google Maps (2025).

Table 2: Investment cost b_i considering assumed service life and operational expenditure.

Feeder Node	3	4	5	6	7	8	9	10	11	12	13	14
Jetty (>=100m)	☑	☒	☑	☑	☒	☑	☑	☑	☒	☒	☒	☑
Container Yard Availability	☒	☒	☒	☒	☑	☑	☒	☒	☑	☒	☑	☒
Equipment Availability	☒	☒	☒	☒	☒	☑	☒	☒	☒	☒	☒	☒
Total Investment Cost (Mil. USD)	0.83	1.23	0.83	0.83	1.07	0.00	0.83	0.83	1.07	1.23	1.07	0.83

Source: Author.

Figure 3: Existing Condition and Optimum Solution Network Structure.



Source: Author.

Table 3: Result Summary.

Rank	Spoke Scheme	Spoke Node	Allocated Feeders	Investment Cost (Mil. USD)	BCR
1	2	8	4,5,6,7,9,10,11,12,13,14	0.83	1.583
		3	5		
2	3	8	4,5,6,7,10,11,12,13	1.66	0.89
		3	5		
		9	14		
3	3	8	4,5,6,7	1.66	0.84
		3	5		
		10	11,12,13		

Source: Author.

3.2. Results and Discussion.

Before running the optimization procedure, the existing condition or the do-nothing cost of the current network must be calculated. In the existing setup, Node 8 operates as the single spoke of the system, as shown in Figure 3a (hub nodes, Node 1 and Node 2, are omitted for clarity). Shipments originate from both hubs, move through Node 8 as the spoke, and are then distributed from Node 8 to all feeder nodes. This arrangement produces a total cost of USD 7.3 million, which is used as the do-nothing cost C^{dnot} for the subsequent analysis.

The optimal spoke location and the allocation of its feeders are determined using the proposed methodology. Figure 3b illustrates the network structure of the optimal solution with its assigned feeders, and Table 3 summarizes the top three solutions. These results capture scenarios with different numbers of spokes in the network. For example, a 2-spoke scheme assigns two feeder nodes as spokes operating in parallel, with each feeder linked to a specific set of feeders. Among the alternatives, the 2-spoke scheme—where Node 8 and Node 3 serve as spokes—delivers the highest benefit–cost ratio (BCR).

From Table 3, it can be observed that the first-ranked solution is the only configuration that produces a benefit–cost ratio (BCR) greater than one. A BCR above one indicates that the implemented network achieves a reduction in total shipping costs compared to the existing condition and is therefore considered beneficial. By contrast, a BCR below one implies that the government's investment in that solution does not generate sufficient benefits to justify the expenditure. Thus, the first-ranked solution represents the optimal configuration, as the benefits of the implemented network justified and exceed the government's investment.

The optimal solution also allows two spoke nodes to operate simultaneously, which provides an important resilience advantage. If one spoke node is disrupted, the other can temporarily function as the single spoke for the entire network. From a governmental perspective, this redundancy is highly valuable, since island networks are frequently exposed to weather-related disruptions. Having a built-in mitigation mechanism is crucial to ensuring the uninterrupted delivery of essential goods to citizens in archipelagic regions.

These findings should also be considered in light of government budget constraints. As shown in Table 3, the optimal solution requires an investment of USD 0.83 million to upgrade the selected nodes so they can function as spoke nodes capable of handling containerized cargo. If the government's available budget is below this level, the network should remain in its current form, which is a 1-spoke scheme configuration with Node 8 serving as the sole spoke. However, if adequate funds are available, implementing the fully optimal network structure would deliver substantial benefits by lowering overall shipping costs across the island network.

From a policy standpoint, introducing the network system in a low-demand island shipping context reduces total transport costs by consolidating cargo flows at the spoke level. In this system, containers are transported from hubs to spokes by container vessels, de-containerized at the spoke, and subsequently distributed as break-bulk cargo to feeder ports. Given the low-demand environment, the government must play a central role in managing shipments and allocating limited resources to support system implementation. Any facility upgrades, such as berth extensions, dredging, yard expansion, and procurement of handling equipment, must be carefully weighed against expected reductions in transport costs, which ultimately translate into lower consumer prices and improved accessibility for island residents.

In the long term, as hinterlands experience rapid development, the government may also encourage private - sector participation, particularly from shipping companies. For shippers, entering the system involves significant investment decisions, including vessel acquisition or chartering, crew costs, and agency overheads at spoke ports. If projected revenues are insufficient to cover these outlays, government support, such as tariff discounts or temporary subsidies, may be necessary to ensure service viability, maintain reliable deliveries of essential goods, and stimulate broader economic development in the hinterland.

Conclusions.

This paper proposes a network-based approach to improving low-demand island shipping by explicitly incorporating investment requirements into the evaluation of network performance. The low-demand nature of island regions necessitates government involvement in managing shipping operations, making investment costs a critical performance indicator. The model builds on the hub-and-spoke framework and extends it by introducing a third-tier feeder node to capture the logistical characteristics of island groups. The optimal spoke location is determined by maximizing the benefit–cost ratio (BCR), where benefits are defined as the reduction in shipping costs relative to the do-nothing baseline, and costs are represented by the investment required for network implementation.

Applying the model to an island network in eastern Indonesia, the result shows that adopting a 2-spoke scheme yields the highest BCR compared to the existing 1-spoke configuration. The resulting BCR is greater than one, demonstrating that the investment is economically justified by the benefits generated. Moreover, the 2-spoke scheme provides a built-in mitigation mechanism, meaning that if one spoke is disrupted, the other can temporarily serve the entire network, ensuring the reliable delivery of essential goods to island residents. This finding underscores the pivotal role of investment considerations in the design and implementation of shipping networks for archipelagic regions. While this study has incorporated investment costs, future research could broaden the analysis by examining alternative funding schemes, including the potential role of lenders in sharing capital costs. Such an extension would be particularly relevant for remote island networks in developing countries, where government fiscal capacity is often constrained.

Disclosure Statement.

No potential conflict of interest was reported by the author(s).

Acknowledgement.

We acknowledge the support of all the participants, the LPDP (Indonesian Endowment Fund for Education) for the financial support from the Indonesian Ministry of Finance; and the Indonesian Ministry of Transportation for the data collection support.

References.

Achmadi, T., Nur, H.I., Banjarnahor, F.N., Kuik, S., Ardhi, E.W., Permana, C.B.S., Riduwan, M., 2021. Connectivity model of archipelagic areas: a case study of Kepulauan Riau. IOP Conf. Series: Earth and Environmental Science 649, 012048.

Amin, C., Mulyati, H., Anggraini, E., & Kusumastanto, T., 2021. Impact of maritime logistics on archipelagic economic development in eastern Indonesia. The Asian Journal of Shipping and Logistics, 27(2), pp. 157-164.

Crotti, D., Ferrari, C., Tei, A., 2022. Understanding the impact of demand shocks on the container port industry. Maritime Economics & Logistics 24, pp. 778-805.

Dijkstra, E. W. (1959). A note on two problems in connexion with graphs. Numerische Mathematik, 1(1), 269–271.

Dukkanci, O., Peker, M. & Kara, B. Y., 2019. Green hub location problem. Transportation Research Part E, 125(2019), pp. 116-139.

Ghaffarinasab, N., Cavus, O., Kara, B. Y., 2023. A mean-CVaR approach to the risk-averse single allocation hub location problem with flow-dependent economies of scale. Transportation Research Part B, 167(2023), pp. 32-53.

Guo, L., Du, J., Zheng, J., He, N., 2023. Integrated Planning of Feeder Route Selection, Schedule Design, and Fleet Allocation with Multimodal Transport Path Selection Considered. Journal of Marine Science and Engineering 11(7).

Humang, W.P., Utomo, D.P., Putra, H., Arianto, D., Pujiwat, R., Sucipto, Upahita, D.P., Fitriana, N., Salsabilla, M.A., Hendra, Y.N.R., Nurhidayat, A.Y., Putri, M.N., Saputro, M.I.A., Santoso, A., Singgih, I.K., Prayogo, D.N., Hapsari, I., Novawanda, O., Soegiharto, S., Arlianto, J.A., 2025. Hub-and-spoke network design to optimize government subsidy costs for maritime transportation in Indonesia. Sustainable Futures 9.

Kisialiou, Y., Gribkovskaia, I., & Laporte, G. (2019). Supply vessel routing and scheduling under uncertain demand. Transportation Research Part C: Emerging Technologies, 104, 305–316.

Kuby, M. J., Gray, R. G., 1993. The hub network design problem with stopovers and feeders: The case of federal express. European Journal of Operational Research 308, 499-524.

Merkel, A., Johansson, M., Lindgren, S., Vierth, I., 2021. How (in)elastic is the demand for short-sea shipping? A review of elasticities and application of different models to Swedish freight flows. Transport Reviews 42 (4), pp. 551-571.

Park, S., Kim, H., Kwon, J., 2023. The impacts of demand and supply shocks in the dry bulk shipping market. The Asian Journal of Shipping and Logistics, 39(1), pp. 13-22.

Placek, M., 2021. Average speed of vessels in the world merchant fleet in 2018, by ship type. Statista. https://www.statista.com/statistics/1268217/average-speed-of-ships-by-ship-type.

Saha, R.C., Khalil, K., 2025. Port connectivity in Asia: A case study on the Hub and Spoke Model for Port Klang and Chattogram Port. Journal of Maritime Research XXII (2), pp. 170-177.

Shareef, A., Taneja, P., van Schuylenburg, M., 2019. Port development in small Island developing states: A case study of the Maldives. In Australasian Coasts and Ports 2019 Conference; Hotel Grand Chancellor Hobart, Australia, 10 - 13 September 2019 (pp. 1334-1340).

Song, D. (2021). A literature review, container shipping supply chain: Planning problems and research opportunities. Logistics, 5 (2), 41 .

Sjafruddin, A., Lubis, H.A.S., Frazila, R.B., & Dharmowijoyo, D., 2009. Policy Evaluation of Multimodal Transportation Network, The Case of Inter Island Freight Transportation in Indonesia. Proceedings of the Eastern Asia Society for Transportation Studies, 7, 2009.

Wang, Y., Wang, N. & Han, P., 2023. Maritime location inventory routing problem for island supply chain network under periodic freight demand. Computers and Operations Research, 149(2023).

Whittaker R. J. & Fernández-Palacios J. M., 2007. Island Biogeography: Ecology, Evolution, and Conservation. New York, Oxford University Press

Wei, H., Sheng, Z., Lee, P.T., 2017. The role of dry port in hub-and-spoke network under Belt and Road Initiative. Maritime Policy & Management, 45(3), pp. 370-387.

Zhou, S. et al., 2023. Hub-and-spoke network design for container shipping in inland waterways. Expert Systems With Applications, 223(2023).

Appendix.

Algorithm 1:

The modified hub-spoke enumeration-based method.

Input: The number of feeder nodes *i*, the number of hub nodes *k*, investment cost for feeder nodes *i* , the do-nothing cost, the Flow Matrix between hub and feeder nodes (w_{ki}), Distance Matrix between nodes (i.e., d_{ki} d_{ik}), the hub-to-spoke link cost, the spoke-to-feeder link cost, the spoke node cost, and the feeder node cost

Output: The optimal spoke location.

1. Generate all possible combinations of spoke selection *j* among feeders *i*. The combinations are constructed in the binary manner, in which 1 represents feeder-to-spoke upgrade on the node, otherwise 0 means the node remains a feeder.
2. **for *y*** = 1 to maximum number of binary combinations
3. Set Hub = *k*
4. Define Spoke and Feeder based on the combinations of binary digit
5. **if** the binary digit is 1, the node is defined as Spoke
6. **else** the node is defined as Feeder
7. **end if**
8. Generate Adjacent Matrix (*i,j*), which has (*i+k*) x (*i+k*) dimension.
9. **if** Adjacent Matrix (*i,j*) connects Hub-and-spoke, or Spoke and Feeder, == 1
10. **else** Adjacent Matrix (*i,j*) == 0
11. **end if**
12. Generate Link Cost Matrix (*i,j*), which has (*i+k*) x (*i+k*) dimension, based on Adjacent Matrix
13. **if** Adjacent Matrix (*i,j*) == 1, Link Cost Matrix (*i,j*) == hub-to-spoke link cost
14. **else** Link Cost Matrix (*i,j*) == spoke-to-feeder link cost
15. **end if**
16. Generate Node Cost Matrix (*i,j*), which has *k* x (*i+k*) dimension
17. **if** Node Cost Matrix (*j*) == Hub, Node Cost Matrix (*i,j*) == 0
18. **else if** Node Cost Matrix (*j*) == Spoke, Node Cost Matrix (*i,j*) == Spoke node cost
19. **else** Node Cost Matrix (*i,j*) == Feeder node cost
20. **end if**
21. Calculate Link Cost Matrix = Distance Matrix multiplied by Link Cost Matrix
22. Generate Spoke-Feeder Assignment using Djikstra's Shortest Path Algorithm (Dijkstra, 1959), combining Adjacent Matrix and Link Cost Matrix. The output of Djikstra's Algorithm is *Costkir*, which represents minimum link cost from each node in accordance with the Adjacent Matrix, and Path, which identifies the shortest path from hub to each feeder, as well as allocated feeder to the selected spoke.
23. Generate Updated Flow Matrix, which is a recalculation of Flow Matrix, where the flow in spoke node is the sum of all its allocated feeder's flow.
24. Calculate Total Link Cost = Sum of *Costkir* multiplied by Flow Matrix
25. Calculate Total Node Cost = Sum of Node Cost Matrix multiplied by Updated Flow Matrix
26. Calculate Total Cost = Total Link Cost plus Total Node Cost
27. Calculate BCR = (Do-Nothing Cost – Total Cost) divided by Investment Cost
28. Select the maximum BCR as optimal solution
29. **end for**

Source: Author, modified from Firdaus et al. (2024)

Table A. Model Input: Annual Demand (TEUs / year).

Node	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	0	0	208	2	0	1	0	1,158	271	2	5	64	2	5
2	0	0	412	1	1	4	2	2,313	184	5	3	55	1	14

Source: Summarized from BauBau Port Authority, 2022.

Table B. Model Input: Distance between Nodes (NM).

Node	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1		459	498	580	587	593	624	628	670	691	702	710	720	919
2			102	187	202	198	234	229	271	290	300	310	321	521
3				110	113	126	162	157	199	218	228	238	249	449
4					31	27	103	58	100	125	131	141	149	339
5						58	104	84	126	158	164	174	182	372
6							48	32	74	103	109	119	127	317
7								68	65	139	145	155	163	353
8									42	86	92	102	110	300
9										128	134	144	152	215
10											20	32	48	229
11												13	29	247
12													16	260
13														273
14														

Source: Author, modified from Google Earth, 2024.

Table C. Model Input: Tariffs.

Parameter	Item	Unit	Amount	Reference
$v^{(1)}$	Average speed of cargo ship	NM/Hours	14	Placek (2021)
$v^{(2)}$	Average speed of container ship	NM/Hours	10	
$m^{(1)}$	Capacity of cargo ship	Tons	90	Operational Data
$m^{(2)}$	Capacity of container ship	TEUs	170	
$g^{(1)}$	Weight of cargo ship	GT	704	
$g^{(2)}$	Weight of container ship	GT	7,800	
f	Capacity of a container	Tons/TEUs	20	
$c^{(1)}$	Unit transportation tariff for cargo ship	USD/ Tons NM	0.54	Assumption
$c^{(2)}$	Unit transportation tariff for container ship	USD/ TEUs NM	3.24	Assumption, using 0.3 ratio (discount factor) to $c^{(1)}$
$s^{(1)}$	Ship to Berth loading/unloading productivity for general cargo	Tons/Hours	10	Operational Data
$s^{(2)}$	Ship to Berth loading/unloading productivity for container	TEUs/Hours	8	
s^{cfst}	De-containerization handling productivity	TEUs/Hours	2	
s^{tran}	Container Transfer (Berth to Yard) productivity	TEUs/Hours	4	
$p^{(1)}$	Time cost for general cargo	USD per Hours per ton	0.002	Sjafruddin et.al (2009)
$p^{(2)}$	Time cost for container	USD per Hours per TEUs	0.039	Calculated from $p^{(1)}$ using f
t^{stor}	Container Storage Duration ()	TEUs/day	5	Operational Data
x^{anch}	Anchorage Tariff	USD/ship weight	0.004	The Decree of Indonesian Transportation Ministry no 15/2016 regarding Tariff for Non-Commercial Port (Decree 15/2016)
x^{bert}	Berth Tariff (USD per ship's GT per *etmal*)	USD/ship weight	0.003	
$x^{(1)}$	Ship to Berth Loading/Unloading Tariff for cargo	USD/ton	0.04	
$x^{(2)}$	Ship to Berth Loading/Unloading Tariff for container	USD/TEUs	0.80	
x^{stor}	Container Storage Tariff	USD per TEUs per day	0.45	
x^{cfst}	Container Stripping/Stuffing Tariff	USD/TEUs	1.13	Adjusted from Equipment Rent Tariff from Decree 15/2016
x^{tran}	Container Transfer (Berth to Yard) Tariff	USD/TEUs	0.56	

Source: Author.