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Integrated Hub-and-Spoke Network Optimization for Inter-Island Freight Distribution in Eastern Indonesia: A Mixed-Method Logistics Framework

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ABSTRACT: Inter-island freight distribution in Eastern Indonesia faces high logistics costs, low vessel utilization, and fragmented freight flows due to dispersed islands, long distances, and weak port-hinterland integration. This study develops an integrated hub-and-spoke logistics framework to improve efficiency by optimizing hub selection, cargo allocation, routing, shipment frequency, and vessel utilization. A mixed-method design combined qualitative stakeholder analysis with logistics network optimization. Semi-structured interviews with twelve stakeholders—shipping companies, port operators, logistics providers, government agencies, cargo owners, and academics—were analyzed thematically to identify operational issues, translated into decision variables for a mixed-integer linear programming optimization framework, complemented by sensitivity analysis of demand variability, fuel prices, vessel capacity, and schedule disruptions. Findings show the existing system remains fragmented and demand-driven, with vessel utilization at 55–65%, below the preferred 80% threshold. Stakeholders identified cargo consolidation, hub-port development, route optimization, scheduling, port-hinterland integration, and digital information sharing as key performance determinants. Strategically located hubs can reduce port calls, improve cargo aggregation, and lower costs, though direct shipping remains suitable for high-volume or time-sensitive cargo—suggesting a hybrid network combining hub-and-spoke and direct routing offers greater flexibility. Digital coordination among stakeholders is essential for schedule reliability. The study concludes that the integrated framework combines stakeholder knowledge with optimization principles, offering practical guidance for reducing costs and strengthening regional maritime connectivity in Eastern Indonesia.

Keywords: Inter-Island Freight Distribution, Hub-And-Spoke Logistics, Maritime Logistics Optimization, Cargo Consolidation, Vessel Utilization, Logistics Network Design, Eastern Indonesia

INTRODUCTION

Indonesia, as the world's largest archipelagic country, depends heavily on maritime transportation to sustain the movement of goods between islands and support national economic integration. The country's logistics system is characterized by a vast network of islands with varying levels of economic development, population density, and transportation infrastructure. These geographical characteristics create unique logistical challenges that distinguish Indonesia from continental countries. In particular, the eastern region of Indonesia consists of numerous dispersed islands separated by considerable maritime distances, making freight distribution highly dependent on efficient maritime logistics networks. Consequently, the effectiveness of inter-island freight transportation has become an important determinant of regional accessibility, market integration, and equitable economic development.

The geographical fragmentation inherent in archipelagic regions directly affects freight distribution efficiency and logistics costs. Previous studies have demonstrated that segmented hinterlands, dispersed coastal nodes, and limited inter-island connectivity significantly influence routing decisions, cargo consolidation opportunities, and transportation performance. Furthermore, the interaction between ports and their hinterlands plays a fundamental role in determining logistics efficiency because congestion, terminal capacity, and inland connectivity collectively shape freight movement across maritime networks (Ahlan et al., 2024; Iannone et al., 2007; Rum, 2018; Sandee, 2016). These findings indicate that the performance of maritime logistics systems cannot be evaluated solely from the perspective of individual ports but must instead be understood as an integrated network connecting supply centers, hub ports, destination ports, and hinterland transportation systems.

Despite continuous improvements in maritime connectivity through national initiatives such as the Sea Toll Program, the distribution of goods throughout Eastern Indonesia remains inefficient. The logistics system continues to experience relatively high transportation costs caused by low cargo consolidation, imbalanced cargo flows, underutilized vessel capacity, uncertain sailing schedules, extended vessel waiting times, port handling inefficiencies, limited transshipment facilities, and inadequate coordination among logistics stakeholders. Interviews conducted in this study further confirm that many vessels serving smaller ports operate below economically desirable utilization levels, while several regional ports experience irregular cargo arrivals and fluctuating demand. Such operational conditions increase transportation costs per shipment and reduce the reliability of freight distribution services. Moreover, weak integration between maritime transportation and hinterland logistics frequently causes delays in cargo delivery despite improvements in maritime connectivity.

The complexity of freight distribution in Eastern Indonesia extends beyond physical infrastructure limitations. Decision making within existing logistics systems is frequently driven by immediate customer demand rather than comprehensive network optimization. Shipping companies commonly determine routes based on operational experience or customer requests without simultaneously considering network-wide interactions among cargo demand, vessel capacity, port performance, and hub selection. As a consequence, some shipping routes remain economically inefficient, while opportunities for cargo consolidation and capacity sharing are not fully utilized. Stakeholders interviewed in this research consistently emphasized that improving logistics efficiency requires integrated planning across shipping companies, ports, freight forwarders, warehouse operators, and government agencies rather than isolated optimization of individual routes or facilities.

Cargo consolidation has been widely recognized as one of the most effective operational strategies for reducing maritime transportation costs. By combining cargo from multiple shippers into larger shipments, transportation providers can increase vessel utilization, reduce unit transportation costs, and improve schedule efficiency. However, achieving effective consolidation remains challenging because customer requirements often prioritize delivery speed over shipment aggregation. Consequently, logistics operators frequently face a trade-off between service responsiveness and transportation efficiency. The interview findings reveal that urgent customer requests often force operators to dispatch partially loaded vessels or containers, reducing overall network efficiency despite increasing operational costs. These practical observations reinforce previous research highlighting cargo consolidation as an essential component of efficient maritime logistics systems.

In response to these operational challenges, logistics researchers have developed numerous optimization methods for freight transportation network design. Vehicle Routing Problems (VRP) and their variants have been extensively applied to determine efficient vessel routing, feeder scheduling, and hub selection, often in combination with Facility Location Problems (FLP) to identify optimal hub locations and network configurations (Dérpich et al., 2024; Gruchmann et al., 2020). Consolidated Location Routing Problem (CLRP) formulations further integrate facility location and routing decisions into a unified optimization framework capable of minimizing total logistics costs. Beyond classical combinatorial optimization, researchers increasingly employ mixed-integer programming, stochastic optimization, robust optimization, and multi-objective optimization to simultaneously consider transportation cost, travel time, service reliability, environmental performance, and demand uncertainty (Dinwoodie et al., 2013; Souza et al., 2019). When exact mathematical solutions become computationally intractable, metaheuristic approaches such as genetic algorithms, simulated annealing, and ant colony optimization have demonstrated strong potential for solving large-scale maritime network optimization problems (Mandal et al., 2021).

Recent advances in maritime logistics have also emphasized digitalization and collaborative decision making. Multi-agent systems and agent-based models have been proposed to facilitate container slot allocation, information sharing, and coordination among ports, shipping companies, freight forwarders, and logistics service providers (Mandal et al., 2021). Such approaches recognize that logistics performance depends not only on physical infrastructure but also on institutional coordination, information transparency, and collaborative planning across multiple stakeholders. These developments are particularly relevant to Eastern Indonesia, where fragmented logistics operations and limited information sharing continue to constrain network efficiency. Accordingly, future logistics systems should integrate operational optimization with digital coordination platforms capable of supporting real-time decision making and capacity sharing.

Although substantial progress has been achieved in maritime logistics optimization, several important research gaps remain(Zhou et al., 2025). First, many optimization studies are based on specific ports or regional case studies, limiting the generalizability of their findings to different archipelagic contexts (Gruchmann et al., 2020; Verny, 2007). Second, empirical operational data including detailed transportation costs, vessel schedules, bunker fuel consumption, and cargo demand are frequently unavailable or proprietary, restricting the calibration and validation of optimization models (Souza et al., 2019; Bektaş et al., 2019). Third, although collaborative logistics and fourth-party logistics (4PL) concepts have attracted increasing attention, existing optimization frameworks rarely incorporate governance structures, trust, incentive alignment, and institutional coordination among multiple logistics actors (Trapp et al., 2020). Finally, environmental considerations, fuel price volatility, and regulatory requirements are increasingly recognized as critical decision variables, yet many optimization models continue to emphasize transportation cost while providing limited integration of sustainability objectives into comprehensive network design (Fahim et al., 2022).

These research gaps are particularly relevant to the logistics system of Eastern Indonesia, where operational performance depends simultaneously on network configuration, stakeholder coordination, infrastructure availability, and demand uncertainty. Existing studies have generally optimized individual logistics components, such as vessel routing, hub selection, or port operations, without integrating these decisions into a comprehensive freight distribution network. Consequently, there remains a need for an optimization framework capable of jointly determining supply-center allocation, hub-port selection, cargo consolidation, shipment routing, vessel capacity utilization, and shipment frequency while considering the operational characteristics of an archipelagic transportation system.

Therefore, this study proposes an integrated hub-and-spoke logistics network for optimizing inter-island freight distribution in Eastern Indonesia. The study combines qualitative evidence obtained from semi-structured interviews with key logistics stakeholders and established concepts from maritime logistics network optimization to develop a comprehensive decision-support framework. Unlike previous studies that focus primarily on isolated operational improvements, this research integrates network design, cargo allocation, hub selection, routing decisions, and vessel utilization into a unified analytical framework. The proposed approach is expected to provide both theoretical and practical contributions by advancing knowledge on integrated maritime logistics optimization while offering policy recommendations for improving logistics efficiency, reducing transportation costs, and strengthening inter-island connectivity in Eastern Indonesia.

METHOD

Research Design

This study adopted a mixed-method research design that integrates qualitative stakeholder analysis with mathematical optimization to develop an inter-island freight distribution network for Eastern Indonesia. The qualitative component was intended to capture operational knowledge, institutional perspectives, and practical constraints that cannot be adequately represented using quantitative operational data alone. The quantitative component translated these qualitative findings into an optimization framework capable of determining efficient hub locations, cargo allocation, shipping routes, and vessel utilization.

The integration of stakeholder analysis and optimization is consistent with recent developments in maritime logistics research, which emphasize that logistics network design should reflect the perspectives of multiple actors, including shipping companies, port operators, freight forwarders, cargo owners, warehouse operators, and government agencies (Trapp et al., 2020; Mandal et al., 2021). Previous studies demonstrate that incorporating stakeholder preferences into optimization models improves model feasibility, practical relevance, and implementation potential because operational decisions are influenced not only by transportation costs but also by governance, institutional coordination, and information sharing (Souza et al., 2019).

The overall research workflow consisted of five sequential stages: (1) qualitative data collection through semi-structured interviews, (2) thematic coding using NVivo, (3) development of optimization variables and constraints, (4) formulation of the hub-and-spoke logistics optimization model, and (5) evaluation of model robustness through sensitivity analysis.

Study Area

The empirical study focused on the **Sulawesi–Maluku distribution corridor**, which represents one of the principal maritime freight corridors in Eastern Indonesia. The corridor was selected because it reflects the operational characteristics of an archipelagic logistics network, including dispersed demand, long maritime distances, multiple feeder ports, and dependence on regional hub ports.

Seven representative ports were selected as network nodes:

- Makassar
- Kendari
- Bau-Bau
- Ambon
- Ternate
- Tidore
- Saumlaki

Makassar and Ambon were considered candidate hub ports because of their strategic locations, relatively larger cargo volumes, and stronger connectivity with feeder ports. The remaining ports functioned as feeder or destination nodes within the proposed hub-and-spoke network.

Data Collection

Primary Data

Primary data were obtained through semi-structured interviews with twelve stakeholders directly involved in inter-island logistics operations. The participants represented shipping companies, port operators, logistics service providers, freight forwarders, warehouse managers, vessel operators, cargo owners, government agencies, and transportation academics.

Semi-structured interviews were selected because they allow respondents to describe operational experiences while maintaining sufficient flexibility to explore emerging issues. This approach also reduces respondent burden and enables the collection of rich contextual information relevant to logistics decision-making, consistent with recommendations for participatory logistics research (Mandal et al., 2021; Trapp et al., 2020).

Interview questions explored:

- existing freight distribution practices;
- hub-port selection;
- cargo consolidation;
- routing decisions;
- vessel utilization;
- shipment frequency;
- transport mode selection;
- logistics cost drivers;
- institutional coordination; and
- digital information sharing.

Secondary Data

Secondary data were collected from official reports, logistics statistics, shipping schedules, port authorities, and government publications. These datasets were intended to complement the interview findings and provide quantitative parameters for the optimization model.

The secondary datasets included:

- cargo demand;
- vessel capacity;
- shipping schedules;
- sailing distance;
- freight transportation costs;
- port handling costs;
- port capacity;
- vessel waiting time;
- hinterland transportation characteristics; and
- geographic network information.

Qualitative Data Analysis

Interview transcripts were analyzed using thematic analysis supported by NVivo software.

Open coding was first applied to identify recurring operational issues. Similar codes were subsequently grouped into broader analytical themes. The final coding framework consisted of major themes including:

- hub-port selection;
- cargo consolidation;
- cargo allocation;
- route optimization;
- vessel utilization;
- shipment frequency;
- logistics cost;
- multimodal integration;
- institutional coordination; and
- service reliability.

These themes were not treated as independent findings. Instead, they served as the conceptual foundation for constructing optimization variables, constraints, and performance indicators. This integration reflects recommendations that qualitative stakeholder knowledge should guide quantitative assumptions, particularly when operational datasets are incomplete or proprietary (Souza et al., 2019; Verny, 2007).

Optimization Model Development

The optimization framework was designed to identify the most efficient inter-island freight distribution network under a hub-and-spoke configuration.

Following previous maritime logistics studies, the model combines hub location and routing decisions within a unified optimization framework (Mandal et al., 2021; McCalla, 2004). This approach integrates concepts from Facility Location Problems (FLP) and Vehicle Routing Problems (VRP), enabling simultaneous determination of hub locations, feeder routes, cargo allocation, and vessel deployment.

Decision Variables

The principal decision variables include:

- selection of supply centers;

- selection of hub ports;
- origin–destination routing;
- cargo allocation;
- shipment frequency;
- vessel assignment; and
- transport mode selection.

Model Parameters

The optimization model incorporates operational parameters including:

- freight demand;
- vessel capacity;
- port handling capacity;
- sailing distance;
- transportation cost;
- port handling cost;
- vessel waiting time;
- fuel cost; and
- shipment frequency.

Objective Function

The objective is to minimize total logistics cost, consisting of:

- maritime transportation cost;
- port handling cost;
- transshipment cost;
- vessel waiting cost;
- fuel cost;
- inventory-related logistics cost; and
- hinterland transportation cost.

Constraints

The model is subject to operational constraints including:

- demand satisfaction;
- supply availability;

- vessel-capacity limits;
- port-capacity limits;
- cargo-flow conservation;
- shipment-frequency requirements; and
- route feasibility.

A Mixed Integer Linear Programming (MILP) formulation was selected because it is widely regarded as one of the most appropriate approaches for integrated hub-location and routing problems of moderate size. Previous studies have demonstrated that MILP-based FLP–VRP hybrid models effectively represent cargo consolidation, feeder routing, and multimodal connectivity while remaining computationally tractable (Huang et al., 2020).

Integration of Stakeholder Knowledge into the Optimization Model

A distinguishing feature of this study is the explicit integration of qualitative stakeholder evidence into the optimization process.

Rather than relying solely on numerical operational data, stakeholder insights were used to:

- identify candidate hub ports;
- determine practical routing constraints;
- establish cargo-consolidation policies;
- define acceptable shipment frequencies;
- prioritize operational objectives; and
- formulate realistic sensitivity-analysis scenarios.

This approach reflects the growing use of participatory logistics planning, where qualitative priorities are translated into optimization objectives, constraints, or scenario assumptions (Gruchmann et al., 2020; Mandal et al., 2021). The integration enhances the realism and policy relevance of the resulting network design.

Sensitivity Analysis

Following optimization, sensitivity analysis was designed to evaluate the robustness of the proposed network under operational uncertainty.

Consistent with previous maritime optimization studies, several complementary approaches were incorporated.

First, local sensitivity analysis examines the influence of incremental changes in key parameters, including transportation costs, port handling costs, fuel prices, and freight demand.

Second, scenario analysis evaluates network performance under alternative operational conditions, including demand growth, fuel-price increases, schedule disruptions, capacity reductions, improved cargo consolidation, enhanced hub performance, and stronger hinterland integration.

Third, threshold analysis identifies parameter values at which the optimal network configuration changes, such as the number of selected hub ports or the transition between direct shipping and hub-and-spoke routing.

Fourth, the study proposes the future application of robust optimization and stochastic optimization to represent demand uncertainty, travel-time variability, and fuel-price fluctuations, as recommended in contemporary maritime logistics research (Souza et al., 2019; Dinwoodie et al., 2013).

Finally, simulation-based evaluation may be incorporated in future work to assess network performance under dynamic operating conditions, complementing deterministic optimization with operational realism (Crainic et al., 2018; Ducruet, 2020).

Research Validity and Reliability

Credibility was enhanced through triangulation of multiple stakeholder groups representing the principal actors within the inter-island logistics system. Interview findings were systematically compared across respondents and integrated with secondary operational data obtained from official sources.

Dependability was supported through a standardized interview protocol and consistent coding procedures in NVivo. Confirmability was strengthened by maintaining a transparent linkage between qualitative themes, optimization variables, and analytical conclusions. Transferability was addressed by selecting a representative inter-island logistics corridor that reflects many operational characteristics of maritime freight distribution in Eastern Indonesia.

The combination of qualitative stakeholder knowledge, optimization modeling, and sensitivity analysis provides a comprehensive methodological framework capable of generating both theoretically rigorous and practically applicable recommendations for improving inter-island freight distribution networks.

RESULT AND DISCUSSION

Characteristics of the Existing Inter-Island Distribution Network

The empirical findings indicate that inter-island freight distribution in Eastern Indonesia is organized around a limited number of major supply and transshipment ports connected to several smaller destination ports. Makassar and, to a lesser extent, Ambon perform strategic functions as supply, consolidation, and transfer nodes, while ports such as Kendari, Bau-Bau, Ternate, Tidore, and Saumlaki operate primarily as feeder, intermediate, or destination nodes. This configuration resembles a partially developed hub-and-spoke network, although the allocation of cargo, shipping routes, and service frequencies is not yet systematically optimized.

The interview evidence shows that current distribution decisions remain strongly influenced by individual customer requests and established commercial practices. Informant 1 explained that origin and destination ports are generally selected according to immediate customer demand rather than through a comprehensive network analysis. Consequently, cargo may be transported through routes that are operationally familiar but not necessarily cost-efficient. Informant 6 similarly reported that the shortest route is not always the least expensive because route performance also depends on sailing frequency, vessel load factor, terminal charges, and service availability.

These observations are consistent with the wider literature on archipelagic freight networks. Inter-island systems commonly develop around major hub ports that consolidate freight from numerous feeder locations and redistribute it to regional destinations (Notteboom & Rodrigue, 2022; Schiller et al., 2014). Such structures generate economies of scale when sufficient cargo can be aggregated at the hub. Nevertheless, the literature also indicates that hub-and-spoke systems may coexist with direct shipping services, particularly where cargo demand is sufficiently concentrated or where time-sensitive freight justifies bypassing intermediate hubs (Trapp et al., 2020; Sun et al., 2022).

The findings therefore suggest that the existing network is neither a fully integrated hub-and-spoke system nor a purely direct-shipping system. Instead, it represents a hybrid configuration that has developed incrementally without unified control over hub selection, feeder routing, cargo consolidation, and shipment frequency. This fragmented structure limits the ability of logistics actors to obtain network-wide economies of scale.

Operational Bottlenecks in Freight Distribution

The interviews identified several interrelated operational bottlenecks. The most frequently reported problems were low cargo consolidation, underutilized vessel capacity, irregular shipping schedules, extended waiting times, limited port facilities, weak hinterland connectivity, and fragmented information sharing.

Informants 3, 10, and 12 emphasized that small shipment volumes are commonly transported separately even though combining cargo from multiple customers could substantially reduce unit costs. Informant 3 noted that logistics operators often postpone departures until a sufficient cargo volume has accumulated. However, customer requests for rapid delivery may force operators to dispatch cargo before an economically efficient load has been achieved. This creates a persistent trade-off between consolidation efficiency and delivery responsiveness.

Vessel capacity utilization emerged as another significant constraint. Informant 1 estimated that vessels on certain routes operate at only approximately 55–65% of capacity, whereas an economically preferable utilization level would exceed 80%. This underutilization increases the transport cost allocated to each container or unit of cargo. Informants 8 and 12 similarly associated uneven vessel arrivals and inappropriate sailing frequency with low utilization. Their responses indicate that excessive frequency with insufficient cargo can be less efficient than a lower but better synchronized service frequency.

The findings also identify port waiting time as an important cost driver. Informant 2 reported that several smaller ports lack adequate cargo-handling equipment and operational capacity, causing vessels to wait longer for berthing, loading, or unloading. Informant 8 observed that ship arrivals are concentrated on certain days, followed by periods of low activity, producing inefficient terminal utilization. These findings correspond with studies identifying dwell time, berth congestion, and handling limitations as major determinants of maritime logistics cost and schedule reliability (Adepoju, 2024; Nwokedi et al., 2021).

Weather and schedule uncertainty further affect network performance. Informant 11 explained that a one-day weather-related delay may disrupt subsequent voyages and increase fuel consumption when vessels attempt to recover the schedule. The effect is therefore cumulative rather than limited to a single route segment. The literature similarly demonstrates that disruptions at ports or shipping services may propagate through interconnected maritime networks, particularly when cargo is concentrated at a small number of hubs (Cullinane, 2011; Giuffrida et al., 2020).

Port Hierarchy and the Role of Regional Hubs

The interview results strongly support the development of a clearer port hierarchy. Informants 1, 2, 5, and 12 stated that regional hub ports are necessary to aggregate cargo from smaller ports before transferring it to mainline services. Informant 1 argued that, without effective hubs, vessels are required to make excessive port calls, increasing voyage time and operating cost. Informant 2 proposed that feeder vessels should consolidate cargo at regional hubs before it is transported by larger vessels.

Within the proposed Sulawesi–Maluku corridor, Makassar is positioned as the principal supply and consolidation hub, while Ambon may function as a regional hub serving Maluku and adjacent island destinations. Kendari and Bau-Bau may serve as feeder or intermediate nodes, whereas Ternate, Tidore, and Saumlaki are more likely to function as regional destination nodes. This classification remains a proposed analytical structure rather than a final optimization result, because complete cargo-demand, capacity, and cost matrices have not yet been incorporated into the mathematical model.

The literature supports the economic logic of this arrangement. Hub ports can increase vessel utilization, standardize port calls, and reduce unit transportation costs through cargo concentration (Gruchmann et al., 2020; Notteboom & Rodrigue, 2008). Nevertheless, the findings also reveal potential risks. Informant 7 expressed concern that freight distribution remains excessively dependent on one or two large ports. Excessive concentration may increase system vulnerability when hubs experience congestion, capacity limitations, or service disruption.

This concern is consistent with previous studies showing that port hierarchies generate both efficiency benefits and systemic risks. Concentrating freight at major hubs improves economies of scale but can also transmit delays and disruptions across feeder services(Viljoen & Joubert, 2016). Thus, the proposed network should include alternative routes or limited direct services for high-volume, high-value, or time-sensitive cargo. The evidence supports a flexible hub-and-spoke structure rather than an inflexible requirement that all cargo pass through a hub.

Cargo Consolidation and Vessel Utilization

Cargo consolidation was one of the most consistently identified mechanisms for improving operational efficiency. Informants 3, 10, and 12 described consolidation as a practical strategy for combining small customer shipments into larger containerized or break-bulk loads. Informant 10 reported that freight forwarders already combine cargo from several customers within a single container, demonstrating that consolidation is operationally feasible.

The findings suggest that consolidation affects three central performance indicators. First, it increases vessel load factors by reducing unused capacity. Second, it lowers transport cost per unit because fixed voyage expenses are distributed across a larger cargo volume. Third, it can reduce the number of low-volume sailings when shipment frequency is coordinated with demand.

However, consolidation also introduces service-level trade-offs. Waiting for cargo accumulation may increase inventory time or delay urgent deliveries. Informant 7 indicated that food distributors often prioritize reliability and delivery speed because delays may increase market prices at the destination. Therefore, consolidation policies should distinguish between regular, non-urgent cargo and time-sensitive commodities. A single consolidation rule would not be appropriate for all commodity types.

The observed relationship between consolidation and utilization supports the design of differentiated service policies. Regular commodities could be assigned to scheduled consolidated services, while urgent or high-value cargo could use direct or higher-frequency options. Such differentiation is consistent with the literature suggesting that direct services may outperform hub-based distribution where cargo concentration or time sensitivity is sufficiently high (Dérpich (Dérpich et al., 2024).

Port–Hinterland Integration and Multimodal Connectivity

The results show that maritime network improvement alone is insufficient to ensure efficient door-to-door distribution. Informant 5 emphasized that maritime services are not consistently integrated with land transportation from ports to hinterland markets. In several cases, shipping capacity is available, but road connectivity, local distribution vehicles, warehousing, or scheduling arrangements remain inadequate.

This finding confirms the importance of port regionalization and intermodal integration. Dry ports, inland container depots, road networks, and other hinterland facilities extend the operational reach of maritime hubs and determine whether cargo can be distributed efficiently after discharge (Rodrigue & Notteboom, 2012; Ducruet & Itoh, 2022). Weak land-side connections may offset savings obtained from maritime consolidation by increasing trucking, storage, and inventory costs.

Accordingly, hub selection should not be based solely on port capacity or geographic position. Candidate hubs should also be evaluated according to hinterland accessibility, warehousing availability, inland transport reliability, and the capacity to serve regional demand. This finding supports the inclusion of hinterland transport cost and connectivity indicators in the optimization framework.

Digital Coordination and Institutional Integration

Digital information sharing emerged as an enabling factor across several interviews. Informant 5 highlighted the need for digital access to shipping schedules, Informant 10 noted that cargo tracking reduces uncertainty, and Informant 12 proposed real-time sharing of vessel capacity information. These findings indicate that physical network optimization must be supported by data integration.

The current system remains institutionally fragmented, with shipping companies, ports, forwarders, warehouses, and government agencies maintaining separate information systems. This fragmentation restricts cargo matching, consolidation planning, and schedule coordination. Digital platforms could improve visibility of available capacity, estimated arrival times, cargo demand, and terminal conditions.

This result is consistent with studies emphasizing that information-sharing platforms and fourth-party logistics systems can improve network synchronization, governance, and reliability (Gruchmann et al., 2020; Mandal et al., 2021). Digital maturity therefore represents both an operational capability and a network-performance variable.

Performance Evaluation Framework

The results indicate that the proposed network should be evaluated using multiple performance measures rather than total cost alone. The relevant indicators derived from interviews and literature are total logistics cost, vessel utilization, transport time, schedule reliability, cargo consolidation ratio, port waiting time, service frequency, hinterland cost, and resilience to disruption.

This multi-dimensional approach is consistent with maritime logistics studies that combine cost, time, reliability, service level, and environmental performance (Mandal et al., 2021). The optimization model can calculate cost and capacity outcomes, while scenario and sensitivity analyses can evaluate the stability of hub selection and routing decisions under changes in demand, fuel price, vessel capacity, and schedule reliability.

At the current stage, only one explicit numerical performance indicator is available from the interviews: vessel utilization of approximately 55–65% on selected routes, compared with a preferred level above 80%. No verified cost reduction, travel-time improvement, or optimal hub allocation has yet been calculated. Accordingly, the present results establish the empirical structure, decision variables, and model assumptions required for subsequent optimization rather than presenting final computational outcomes.

Synthesis of Empirical Findings

The combined findings show that Eastern Indonesia's inter-island freight system is characterized by partial hub concentration, fragmented routing, weak consolidation, low capacity utilization, schedule uncertainty, and insufficient port–hinterland integration. Regional hubs can improve efficiency by consolidating cargo and reducing unnecessary port calls, but excessive dependence on a limited number of hubs may create congestion and resilience risks.

The empirical evidence therefore supports a hybrid and adaptive network design. Regular cargo flows should be consolidated through strategically selected hubs, whereas sufficiently large or time-sensitive shipments may be assigned to direct services. The resulting optimization model should simultaneously determine hub selection, cargo allocation, route activation, vessel deployment, and shipment frequency while accounting for port capacity, hinterland accessibility, and operational uncertainty.

These findings provide the substantive basis for comparing the existing distribution configuration with an optimized hub-and-spoke network once complete operational datasets become available.

The findings demonstrate that improving inter-island freight distribution in Eastern Indonesia requires an integrated network perspective rather than the isolated optimization of individual routes, ports, or vessels. The current system is characterized by partial hub concentration, fragmented cargo flows, low vessel utilization, irregular service frequency, weak port–hinterland integration, and limited information sharing. These conditions confirm that maritime logistics performance is produced by interactions among multiple actors, including shipping companies, port operators, freight forwarders, cargo owners, warehouse managers, and public authorities. Accordingly, the proposed hub-and-spoke framework extends conventional maritime logistics theory by incorporating operational, institutional, and governance dimensions within a unified network design. This is consistent with studies emphasizing that logistics decisions are shaped by data availability, organizational incentives, coordination mechanisms, and coopetition among stakeholders, rather than by cost minimization alone (Mandal et al., 2021; Trapp et al., 2020; Gruchmann et al., 2020).

The empirical results particularly support the theoretical importance of cargo consolidation. Interview evidence indicated that many shipments are dispatched in relatively small volumes, producing vessel utilization of approximately 55–65% on selected routes. From a network perspective, such underutilization reflects not only insufficient cargo volume but also inadequate coordination of departure times, customer demand, vessel capacity, and feeder services. A hub-and-spoke system can address this problem by aggregating cargo from several origins before assigning it to larger vessels. When properly coordinated, this arrangement can distribute fixed voyage costs across larger shipment volumes, improve schedule regularity, and reduce unnecessary port calls. These benefits are consistent with the established logic of hub consolidation and feeder optimization (Notteboom & Rodrigue, 2008; Gruchmann et al., 2020; Dérpich et al., 2024; Viljoen & Joubert, 2016).

However, the findings also show that hub-based distribution should not be applied uniformly. Informants representing cargo owners emphasized that delivery reliability may be more important than the lowest possible freight rate, particularly for food and other time-sensitive goods. Waiting for additional cargo to achieve a higher load factor may reduce transportation cost while increasing inventory time, market risk, or spoilage. Previous studies similarly indicate that direct routes can outperform hub-dominant configurations when cargo volumes are sufficiently concentrated or when transshipment creates unacceptable time and handling penalties (Dérpich et al., 2024; Sun et al., 2022). The most appropriate structure for Eastern Indonesia is therefore likely to be a hybrid network in which regular and fragmented cargo is consolidated through hubs, while high-volume, urgent, or high-value shipments may bypass intermediate nodes. This interpretation modifies a purely hierarchical conception of hub-and-spoke logistics by emphasizing adaptive routing according to cargo characteristics and service requirements.

The proposed designation of Makassar as a principal hub and Ambon as a potential regional hub is supported by their strategic positions within the Sulawesi–Maluku corridor. Nevertheless, the benefits of port hierarchy depend on more than geographic centrality. Hub efficiency requires sufficient terminal capacity, reliable feeder connections, predictable schedules, and effective hinterland access. The interviews showed that smaller ports experience inadequate cargo-handling facilities, irregular vessel arrivals, and extended waiting times, while land-side distribution is often poorly synchronized with maritime services. This supports the argument that port performance must be evaluated as part of a broader port–hinterland system. Dry ports, inland container depots, warehousing, and reliable road or rail connections can extend the functional reach of maritime hubs and reduce friction between sea and inland transport (Rodrigue & Notteboom, 2012; Ducruet & Itoh, 2022; Ahlan et al., 2024; Iannone et al., 2007).

At the same time, concentration at a limited number of hubs creates resilience concerns. Congestion, infrastructure failure, severe weather, or schedule disruption at a central port may propagate through the entire feeder network. The interview findings concerning weather-related delays and cascading schedule changes illustrate this vulnerability. Integrated network optimization therefore needs to incorporate alternative routes, reserve capacity, and disruption scenarios rather than maximizing efficiency under normal conditions only. This advances maritime-network theory by linking consolidation benefits with resilience trade-offs. Robust, stochastic, and scenario-based optimization methods can evaluate whether a network remains effective under fluctuating demand, fuel-price changes, port congestion, and vessel-capacity reductions (Bai & Fan, 2022; Ducruet, 2020).

The results also highlight the managerial importance of digital coordination. Cargo consolidation and dynamic routing require timely information on cargo availability, vessel capacity, expected port arrival, terminal congestion, and inland transport readiness. Yet the interviews indicated that logistics actors often operate through separate information systems. Digital freight platforms, port-community systems, and fourth-party logistics arrangements could enable real-time capacity matching, coordinated scheduling, and shared cargo visibility. Such systems may reduce uncertainty and improve vessel utilization without necessarily requiring immediate large-scale infrastructure expansion (Gruchmann et al., 2020; Mandal et al., 2021; Sun et al., 2022). For shipping companies, the practical implication is that hub placement should be accompanied by feeder-route optimization, differentiated service policies, performance dashboards, and disruption-aware planning. Relevant indicators include vessel load factor, berth waiting time, cargo dwell time, on-time performance, service frequency, unit logistics cost, and emissions.

Public policy is equally important because individual firms cannot independently resolve infrastructure gaps, regulatory fragmentation, and interoperability barriers. Effective interventions include strengthening regional ports through scalable handling equipment, improving hinterland connectivity, simplifying port-clearance procedures, coordinating policy across agencies, and establishing common data-sharing standards. These measures are supported by research on dry ports, port regionalization, terminal capacity, and governance reform (Rodrigue & Notteboom, 2012; Adepoju, 2024; Nwokedi et al., 2021). Environmental incentives should also be incorporated because fuel consumption, route structure, vessel speed, and capacity utilization influence both cost and emissions. A policy framework that combines economic efficiency with environmental targets would align network optimization with broader sustainable-maritime objectives (Trapp et al., 2020; Dérpich et al., 2024).

Finally, emerging technologies provide opportunities to strengthen the proposed framework. Mixed-integer programming can be combined with decomposition, simulation-optimization, and agent-based approaches to solve larger and more dynamic networks. Artificial intelligence and machine learning may improve demand forecasting, fuel-consumption estimation, port-call prediction, and disruption detection, while network science can identify critical hubs and vulnerable connections (Crainic et al., 2018; Ducruet et al., 2018). Digital twins, Petri-net models, and maritime Internet of Things systems may further support real-time monitoring and scenario testing (Kabashkin & Sansyzbayeva, 2024). Nevertheless, these technologies will only generate meaningful improvements when supported by reliable data, institutional trust, interoperable systems, and clearly defined decision responsibilities.

Overall, the study contributes to maritime logistics knowledge by linking hub selection, cargo consolidation, vessel utilization, feeder routing, hinterland integration, digital coordination, and resilience within a single conceptual framework. Its principal implication is that logistics efficiency in Eastern Indonesia should not be pursued through a single infrastructure project or routing adjustment. It requires an adaptive network in which physical assets, operational decisions, stakeholder incentives, and information systems are jointly coordinated.

CONCLUSION

This study examined the optimization of inter-island freight distribution in Eastern Indonesia through a hub-and-spoke logistics approach. The findings show that the current distribution system remains fragmented and operationally inefficient due to low cargo consolidation, underutilized vessel capacity, irregular shipping schedules, extended waiting times, limited port facilities, weak port–hinterland integration, and inadequate information sharing among logistics actors. The evidence also indicates that freight flows are concentrated around a limited number of major ports, while smaller ports continue to experience unstable cargo volumes and uneven service frequency.

The study demonstrates that an integrated network perspective is more appropriate than the isolated optimization of individual routes or ports. A hub-and-spoke configuration can improve distribution performance by consolidating cargo, reducing unnecessary port calls, increasing vessel utilization, and coordinating feeder services. However, the findings also suggest that a fully centralized hub system may not be suitable for all cargo types. Time-sensitive, high-value, or sufficiently concentrated shipments may require direct services, while fragmented and regular cargo flows are more appropriate for hub-based consolidation. Therefore, the most suitable configuration for Eastern Indonesia is an adaptive hybrid network that combines hub-and-spoke and direct-routing strategies.

The principal scientific contribution of this research lies in the development of an integrated framework that links hub selection, cargo allocation, route design, shipment frequency, vessel utilization, hinterland connectivity, institutional coordination, and resilience. Unlike approaches that focus solely on transportation cost or route length, the proposed framework incorporates qualitative stakeholder knowledge into the design of a mathematical optimization model. This integration strengthens the practical relevance of the model and expands maritime logistics theory by recognizing that network performance depends on operational, institutional, and informational conditions.

The study also provides several practical implications. Shipping companies should coordinate feeder routes, consolidate compatible cargo, differentiate services according to urgency, and monitor key performance indicators such as load factor, dwell time, schedule reliability, and unit logistics cost. Port operators should improve handling capacity, balance vessel arrivals, and reduce waiting time. Government agencies should strengthen regional hubs, improve hinterland connectivity, simplify regulatory procedures, and establish interoperable digital information systems. Real-time sharing of vessel capacity, cargo availability, port conditions, and sailing schedules may significantly improve network coordination and reduce uncertainty.

The proposed framework has important policy implications for the development of maritime connectivity in Eastern Indonesia. Infrastructure investment should not focus exclusively on major ports but should also strengthen feeder ports, inland distribution systems, warehousing, and road connections. Policy interventions should support scalable port infrastructure, digital logistics platforms, data-sharing standards, and collaborative governance across institutions. Environmental considerations, including fuel efficiency and emissions, should also be incorporated into future network-design decisions.

This study is limited by the absence of complete quantitative data on origin–destination demand, route-specific costs, vessel capacity, port throughput, handling time, and sailing reliability. Consequently, the current findings establish the conceptual and empirical foundations of the optimization model rather than presenting final computational results. Future research should implement the proposed framework using a complete operational dataset and compare alternative hub configurations under demand, fuel-price, capacity, and disruption scenarios. Further studies should also explore robust and stochastic optimization, simulation-optimization, digital twins, and machine-learning applications for demand forecasting and disruption prediction.

Overall, this research contributes to existing knowledge by demonstrating that efficient inter-island freight distribution requires the coordinated design of physical networks, operational decisions, stakeholder relationships, and digital information systems. The proposed adaptive hub-and-spoke framework offers a practical basis for reducing logistics costs, improving vessel utilization, enhancing service reliability, and supporting more balanced regional connectivity across Eastern Indonesia.

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