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Developing a Port Handling Model to Support Cross-Docking in Archipelagic Logistics: A Discrete-Event Simulation Study

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Abstract

Purpose: Indonesia's archipelagic geography creates long lead times, high logistics costs, and persistent container dwelling time at major ports. This study develops and evaluates a port-handling model that supports cross-docking to reduce dwelling time and improve inter-island distribution performance. **Research design, data and methodology:** A multi-level framework is implemented as a discrete-event simulation of Batu Ampar Port (Batam) as a representative domestic container hub. The model integrates material, information, and financial flows and is parameterised using port operational data and national statistics. Scenario experiments compare a baseline storage-oriented system with cross-docking-oriented configurations under demand shocks, route delays, and supply disruptions, supported by expert review and variance-based output analysis. **Results:** Cross-docking-oriented handling reduces simulated dwelling time and total distribution lead time from major origin ports to surrounding islands while preserving realistic system behaviour. Key bottlenecks concentrate in job-order processing, truck arrivals, and outbound ferry capacity, particularly on routes to Natuna and Anambas. The model is robust to cost-parameter changes but sensitive to capacity and availability shocks. **Conclusions:** Port handling is a strategic lever in archipelagic logistics. Cross-docking supported by integrated information systems and targeted capacity upgrades on critical routes can improve efficiency and reliability and strengthen domestic maritime connectivity.

Keywords : Archipelagic Logistics, Cross Docking, Port Handling, Discrete-Event Simulation, Indonesia

JEL Classification Code: R41, L91, L92, C63

1. Introduction

Indonesia's rapid economic and industrial growth has placed strong pressure on its logistics and distribution systems, particularly in an archipelagic setting characterised by more than 17,000 islands and uneven population distribution (Aritonang et al., 2025). Java is densely populated and relatively well connected, whereas regions such as Maluku and Papua still face limited infrastructure and high transport frictions (Setiawan, 2018). These structural conditions lead to longer delivery times, higher inventory requirements, and logistics costs that average about 14.08 percent of sales value, well above benchmark countries such as Japan (Subiyanto & Suyoto, 2020). Inadequate road networks, constrained port capacities, and weather-related disruptions further undermine Indonesia's

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trade competitiveness and equitable regional development (Pamadi & Sari, 2022; Amin et al., 2021).

In this context, more effective distribution models are urgently required, especially for island regions where logistics constraints are most acute. Cross docking has been widely recognised as a promising strategy to reduce storage, shorten lead times, and lower overall logistics costs by transferring goods directly from inbound to outbound transport with minimal or no warehousing (Han-chuan et al., 2013; Buijs et al., 2016). By consolidating shipments and coordinating arrival and departure schedules, cross docking can improve fleet utilisation, compress order cycle times, and enhance customer service (Gallo et al., 2022; Baniamerian et al., 2018). For a country where shipping times to Maluku and Papua can reach 10–20 days compared with 1–4 days in the Jakarta and West Java areas, these efficiency gains are particularly relevant (Anizar et al., 2025; Cahyo et al., 2023).

Beyond economic benefits, cross docking in island logistics also has social and environmental implications. More streamlined distribution can help reduce regional price disparities for essential goods and improve access for communities in peripheral regions (Zulfikri, 2025; Rezaei & Kheirkhah, 2017). At the same time, better shipment consolidation can lower fuel consumption and emissions, contributing to smaller carbon footprints and more sustainable logistics systems (Mostafa & Eldebaiky, 2023; Abad et al., 2018). However, the full potential of cross docking in this context depends on the ability to adapt the concept to the geographical and infrastructural realities of archipelagic transport.

Cross docking gained prominence in the 1990s and has since attracted extensive research in truck scheduling, dock assignment, and routing decisions (Agustina et al., 2010). The core principle is to transfer products from inbound to outbound doors without long-term storage, typically within less than 24 hours, thereby eliminating many traditional warehousing functions and reducing inventory levels (Yu & Egbelu, 2008; Alpan-Gaujal et al., 2011). Most existing models, however, have been developed for large continental or predominantly land-based geographies such as the United States, France, and China, where trucks can be rescheduled and rerouted with relatively high flexibility (Chargui et al., 2020; Serrano et al., 2021; Wisittipanich et al., 2019; Ye et al., 2018).

By contrast, distribution in archipelagic regions is constrained by fixed shipping routes and schedules, limited port infrastructure, and higher uncertainty in sailing and handling times. National shipping lines typically operate predetermined routes that cannot be easily altered, yet voyage times still vary because of weather, congestion, and port conditions. These rigid but uncertain conditions, combined with first-come, first-served berthing practices, create an operational environment that is fundamentally different from that assumed in most cross-docking models. Product-related characteristics such as item type, value, expiry date, and physical dimensions, together with facility capacities and regional infrastructure, strongly influence feasible handling configurations in island settings (Savchenko & Kuzmenko, 2018; Nurprihatin et al., 2021; Noviyanti et al., 2025; Machaca et al., 2025). From a systems perspective, these factors interact with the three fundamental flows of cross-docking systems, namely material, financial, and information flows, which must be integrated to achieve reliable performance (Coindreau et al., 2021; Chargui et al., 2017).

Empirical evidence shows that despite national initiatives such as the Tol Laut programme, price gaps for basic commodities and fuel between eastern Indonesia and Java remain substantial, largely because of long transit times and high logistics costs (Kurniawan et al., 2024; Mawikere & Herijanto, 2023; Sa'adah, Yakti, & Susanto, 2019; Triantoro, 2020). Containerised cargo flows through 33 major ports are very large, whereas air cargo volumes are relatively small, reinforcing the central role of seaports in national distribution (Irawati et al., 2025; Aqmarina & Achjar, 2018; Syafaaruddin, 2015). Yet port performance indicators such as dwelling time remain higher in many Indonesian ports than in leading international ports, with averages of about 2.6 to more than 5 days compared with 1 to 3 days in ports such as Singapore and Shanghai (Nugroho et al., 2024; Gurning & Riadi, 2022; Sirajuddin, 2020). These delays increase logistics costs and undermine the potential benefits of cross-docking-based distribution.

Recent studies stress that cross docking in archipelagic contexts must be supported by robust information systems and decision-support tools that provide visibility over cargo status, schedules, and capacity constraints (Chargui et al., 2020; Vahdani & Zandieh, 2010). Analytical and optimisation-based approaches, including queueing models and heuristic algorithms, have been proposed to tackle cross-dock design and operation, but most remain focused on inland facilities and truck-based networks (Rostami et al., 2022). Ports, however, are critical nodes in an island country: they function not only as transfer points but also as logistics hubs where customs clearance, temporary storage, and cargo consolidation take place (Riadi & Depitasari, 2025). Efficient quay and yard operations, crane scheduling, and internal transport are essential to minimise vessel and container waiting times (Kizilay & Eliiyi, 2020).

Against this backdrop, existing cross-docking models do not adequately capture the specific constraints of archipelagic logistics, the central role of port handling processes in domestic distribution, or the joint management of material, financial, and information flows in such settings (Belle et al., 2012; Briesemeister & Novaes, 2017). This study addresses that gap by developing and evaluating a port-handling model specifically designed to support cross docking in an archipelagic logistics context. Focusing on the incoming process at seaports in Indonesian island regions, the research identifies and structures the key stages of a port-handling model that supports cross docking and examines how this model can be implemented optimally to minimise dwelling time and improve distribution performance. The model incorporates product characteristics, facility capacities, geographical factors, and integrated information flows, and is evaluated through discrete-event simulation. In doing so, the paper extends cross-docking theory to a port-centric, archipelagic setting and offers practical insights for policymakers, port authorities, and logistics practitioners seeking to redesign handling processes in Indonesia's island logistics system.

2. Literature Review

2.1. Supply Chain and Maritime Logistics in Archipelagic Context

Supply chain management (SCM) has evolved from an internal logistics perspective toward an inter-organizational discipline that coordinates material, information, and financial flows across suppliers, manufacturers, distributors, logistics providers, and customers (Mostafa & Eldebaiky, 2023; Rezaei & Kheirkhah, 2017). Modern SCM emphasizes integration, agility, and alignment of incentives to simultaneously improve cost, speed, reliability, and flexibility, particularly in environments where disruptions at one node can propagate throughout the chain (Belle et al., 2012; Buijs et al., 2016; Gallo et al., 2022; Vahdani & Zandieh, 2010). Within this framework, maritime logistics is a critical component in countries that depend heavily on sea transport, with ports acting as key nodes linking sea and land transport and strongly influencing logistics costs, transit times, and service reliability (Amin et al., 2021; Aritonang et al., 2025; Sa'adah et al., 2019; Triantoro, 2020). In many developing and archipelagic economies, congestion, limited capacity, and high container dwelling times remain major obstacles to performance (Gurning & Riadi, 2022; Nugroho et al., 2024; Nur et al., 2019; Setiawan, 2018), and these challenges are intensified in Indonesia, where fragmented demand across thousands of islands, long sailing distances, and weather-related risks require tighter integration between network design, ship scheduling, and port operations (Cahyo et al., 2023; Kurniawan et al., 2024; Pamadi & Sari, 2022; Irawati et al., 2025; Syafaaruddin, 2015).

For an archipelagic country, these supply chain considerations converge at the port node, where sea and land flows meet and where delays immediately translate into higher inventory and logistics costs. In Indonesia, the combination of fragmented island demand, long sailing distances, and weather-related risks makes ports not only gateways for international trade but also critical hubs for domestic redistribution (Amin et al., 2021; Aritonang et al., 2025; Cahyo et al., 2023; Kurniawan et al., 2024; Pamadi & Sari, 2022; Sa'adah et al., 2019; Triantoro, 2020). This study therefore treats ports as central leverage points for cross-docking-based improvements in archipelagic supply chains, integrating maritime logistics concepts with port-handling process design to reduce dwelling time and support more reliable multi-island distribution (Gurning & Riadi, 2022; Nugroho et al., 2024; Nur et al., 2019; Irawati et al., 2025; Zulfikri, 2025).

2.2. Cross Docking as an Advanced Distribution Strategy

Cross docking is an advanced distribution strategy in which inbound shipments are unloaded, sorted, and directly transferred to outbound vehicles with minimal or no storage, typically within less than 24 hours (Agustina et al., 2010; Belle et al., 2012; Machaca et al., 2025). Its primary objective is to compress lead time and reduce inventory holding by eliminating a large share of traditional warehousing functions, thereby lowering transportation and storage costs, reducing stock levels, and improving responsiveness to demand (Han-Chuan et al., 2013; Mostafa & Eldebaiky, 2023; Savchenko & Kuzmenko, 2018). The cross-docking literature spans several research streams, including truck scheduling and dock assignment, layout design and product allocation within cross-dock facilities, and integrated routing and scheduling of inbound and outbound vehicles in distribution networks, often addressed through mathematical programming and heuristic approaches (Alpan-Gaujal et al., 2011; Coindreau et al., 2021; Gallo et al., 2022; Vahdani & Zandieh, 2010; Wisittipanich et al., 2019; Ye et al., 2018; Yu & Egbelu, 2008). More recent work has incorporated sustainability objectives, such as emission reduction and energy savings through shipment consolidation and optimized vehicle movements (Abad et al., 2018; Mostafa & Eldebaiky, 2023; Rezaei & Kheirkhah, 2017; Serrano et al., 2021), yet both reviews and case studies indicate that maritime and port-centric applications remain far less explored than truck-based, inland networks (Amin et al., 2021; Gurning & Riadi, 2022; Pamadi & Sari, 2022; Zulfikri, 2025).

However, the overwhelming majority of cross-docking studies have been developed for inland truck-based networks, where routing and scheduling decisions can be optimized with high flexibility and where infrastructure conditions are relatively homogeneous (Baniamerian et al., 2018; Briesemeister & Novaes, 2017; Rostami et al., 2022;

Wisittipanich et al., 2019; Yu & Egbelu, 2008). These settings differ markedly from archipelagic logistics, where vessel routes and schedules are largely fixed and port handling is subject to regulatory and infrastructural constraints (Amin et al., 2021; Cahyo et al., 2023; Kurniawan et al., 2024; Pamadi & Sari, 2022). As a result, existing cross-docking models provide limited guidance on how cross-docking principles should be adapted when the main consolidation node is a seaport rather than an inland terminal, and when uncertainty stems from maritime conditions and port operations rather than from road traffic or truck scheduling (Gurning & Riadi, 2022; Mawikere & Herijanto, 2023; Nugroho et al., 2024; Nur et al., 2019).

2.3. Cross Docking in Archipelagic and Port-Centric Settings

Most cross-docking studies have been conducted in countries with predominantly land-based geographies, where trucks can be rescheduled and rerouted with relatively high flexibility, enabling multi-objective optimisation of arrival patterns, loading sequences, and departure schedules (Abad et al., 2018; Belle et al., 2012; Buijs et al., 2016; Vahdani & Zandieh, 2010; Wisittipanich et al., 2019; Ye et al., 2018; Yu & Egbelu, 2008). In contrast, archipelagic logistics is characterised by fixed sea lanes, predetermined ship schedules, and limited alternative routes, which reduce operational flexibility and amplify the impact of delays (Amin et al., 2021; Cahyo et al., 2023; Kurniawan et al., 2024; Sa'adah et al., 2019; Triantoro, 2020). Beyond transport constraints, product characteristics such as type, value, physical dimensions, and expiry date affect handling requirements, prioritisation rules, and risk profiles, while facility capacities - including berth availability, yard and warehouse space, equipment levels, and hinterland connectivity - constrain feasible cross-docking configurations (Agustina et al., 2010; Han-Chuan et al., 2013; Setiawan, 2018; Subiyanto & Suyoto, 2020). From a systems perspective, these factors interact with the three fundamental flows of cross-docking systems, namely material, financial, and information flows, and the integration of information flows is particularly crucial for real-time coordination and reliable performance in island environments that are highly exposed to maritime uncertainty (Mostafa & Eldebaiky, 2023; Nur et al., 2019; Nurprihatin et al., 2021; Rezaei & Kheirkhah, 2017; Gurning & Riadi, 2022).

In archipelagic contexts, therefore, cross docking cannot be conceptualised solely as an internal warehouse process; it must be embedded within port-handling operations that are constrained by fixed shipping routes, yard capacities, and complex documentation requirements (Amin et al., 2021; Kurniawan et al., 2024; Mawikere & Herijanto, 2023; Pamadi & Sari, 2022; Sa'adah et al., 2019). This study positions port-centric cross docking as an integrated handling concept that connects vessel schedules, yard operations, and outbound feeder services in a single framework. By doing so, it responds to calls in the logistics and maritime literature for more context-specific models that account for geographical fragmentation, multi-modal interfaces, and regulatory complexity in island logistics (Aritonang et al., 2025; Gurning & Riadi, 2022; Nugroho et al., 2024; Irawati et al., 2025; Zulfikri, 2025).

2.4. Port Handling, Dwelling Time, and Simulation-Based Modelling

Ports are critical nodes in maritime and archipelagic logistics because they connect sea and land transport, provide customs and regulatory services, and increasingly function as logistics hubs for consolidation, temporary storage, and value-added activities (Amin et al., 2021; Aritonang et al., 2025; Setiawan, 2018; Irawati et al., 2025). Operationally, port handling consists of a sequence of activities including vessel berthing, loading and unloading, yard operations, administrative procedures, and gate operations, where inefficiencies at any stage increase vessel turnaround time and container dwelling time (Aqmarina & Achjar, 2018; Gurning & Riadi, 2022; Nur et al., 2019; Syafaaruddin, 2015). Empirical studies on Indonesian ports indicate that average dwelling times in major gateways such as Tanjung Priok, Tanjung Perak, Belawan, Makassar, and Batu Ampar still range from about three to more than five days, longer than international benchmarks and a persistent source of high logistics costs (Gurning & Riadi, 2022; Nugroho et al., 2024; Pamadi & Sari, 2022; Setiawan, 2018). Given the very large container flows handled by the national port system and the relatively small share of air cargo, improving port handling performance is therefore crucial for the efficiency of archipelagic logistics and for the success of initiatives such as the sea-toll programme, bonded logistics centres, and regional hub development (Kurniawan et al., 2024; Mawikere & Herijanto, 2023; Riadi & D., 2025; Sa'adah et al., 2019).

Discrete-event simulation (DES) is widely used to analyse complex logistics systems with stochastic arrivals, queues, and resource constraints, including ports, terminals, and cross-docking facilities, because it allows alternative configurations and policies to be tested without disrupting real operations (Ahmadizar et al., 2015; Briesemeister & Novaes, 2017; Gallo et al., 2022; Hasani Goodarzi et al., 2022; Pan et al., 2021; Rostami et al., 2022; Zhang, 2021). DES is particularly suitable for studying port-handling systems where arrivals, queues, and service times are stochastic and where multiple resources such as berths, yard equipment, and trucks interact over time (Hermansyah et al., 2025; Mostafa & Eldebaiky, 2023; Rezaei & Kheirkhah, 2017). However, most existing DES applications in ports focus on operational indicators such as crane utilisation or vessel turnaround, without explicitly modelling the integration of material, information, and financial flows within a cross-docking-oriented configuration (Belle et al., 2012; Coindreau et al., 2021; Nurprihatin et al., 2021). By combining DES with a multi-level conceptual framework, the present study develops a port-handling model that captures these three flows simultaneously, thereby extending simulation-based port and cross-docking research beyond traditional throughput and capacity analyses (Mostafa & Eldebaiky, 2023; Rezaei & Kheirkhah, 2017; Rostami et al., 2022).

2.5. Research Gap and Conceptual Positioning

The literature review reveals three main gaps. First, cross-docking research is dominated by land-based, truck-intensive contexts with flexible routing and scheduling, while studies explicitly addressing archipelagic logistics with fixed sailing schedules and port constraints remain scarce. Second, port-operation studies rarely embed cross-docking principles into quay and yard processes, even though ports in island nations are natural candidates to act as cross-docking hubs linking main islands with peripheral regions. Third, although discrete-event simulation has been widely applied to terminal and cross-dock operations, there is a lack of models that jointly capture material, information, and financial flows in port-centric cross-docking systems operating under probabilistic maritime conditions.

To address these gaps, this study proposes a multi-level, port-centric cross-docking model tailored to the Indonesian archipelago. The model explicitly decomposes total distribution time into schedule-related, route-related, and storage-related components, integrates cargo characteristics, facility capacities, and geographical factors, and embeds information and financial flows into the handling stages. Implemented via discrete-event simulation and empirically instantiated at Batu Ampar Port, the model aims to demonstrate how redesigned port-handling processes can reduce dwelling time, improve route efficiency, and enhance the reliability of multi-island distribution networks.

3. Methodology

3.1. Research Design

This study adopts a modelling and simulation research design based on discrete-event simulation (DES), which is widely used to analyse complex logistics systems with stochastic arrivals, queues, and constrained resources in cross-docking and port-related contexts (Gallo et al., 2022). The research process comprises five stages: defining the problem and system boundaries for port handling within an archipelagic cross-docking network; developing a multi-level conceptual model (strategic, tactical, operational) to capture network structure, capacity allocation, and detailed handling processes; translating this conceptual model into a formal DES model by specifying entities, events, process logic, and parameter values; validating and verifying the model through expert-based content assessment and comparison of simulated outputs with empirical patterns; and finally, conducting scenario and sensitivity analyses to evaluate system performance under alternative handling configurations and parameter variations. The unit of analysis is the port-handling system at container terminals serving inter-island domestic flows, with a specific focus on incoming (unloading) processes in archipelagic settings where port performance and dwelling time are critical concerns (Amin et al., 2021; Gurning & Riadi, 2022; Nugroho et al., 2024). DES is selected because it allows experimentation with alternative port-handling and cross-docking configurations without disrupting real operations, capturing the interaction of resources and queues at a high level of detail while ensuring consistency with broader network design decisions and capacity policies (Belle et al., 2012).

3.2. Case Study: Batu Ampar Port

Batu Ampar Port in Batam is selected as the empirical case study because it is one of the main container ports in western Indonesia and exhibits representative characteristics of archipelagic logistics, including relatively high average dwelling times (above three days), complex inter-island container flows, and capacity constraints. As a gateway connecting major production and consumption centres in the western part of the archipelago, Batu Ampar handles significant volumes of domestic containerised cargo and operates under standard national SOPs for documentation and customs clearance, making it directly affected by national programmes to improve inter-island connectivity. These characteristics make Batu Ampar an appropriate testbed for a port-centric cross-docking model whose structure and parameterisation can later be calibrated and transferred to other large Indonesian ports with similar functional roles and operational profiles, such as Belawan, Makassar, Tanjung Perak, and Tanjung Priok, thereby enhancing the generalisability and practical applicability of the research findings.

3.3. Data Collection and Parameters

The discrete-event simulation model represents the main handling stages, queues, and resource constraints at Batu

Ampar Port within a cross-docking-oriented distribution concept. It captures vessel arrivals following fixed schedules with stochastic deviations around planned arrival times, berth and crane allocation subject to capacity limits and operating rules, internal transport processes between berths, yard areas and cross-docking zones, documentation and customs procedures that may introduce additional delays, and gate-out operations that link port handling to inland and inter-island distribution legs. Several experimental scenarios are designed to compare the current handling system with alternative configurations: Scenario 0 represents existing conditions with traditional port operations and limited cross-docking integration; Scenario 1 reconfigures handling sequences to prioritise direct transfer from vessel to outbound transport whenever feasible, subject to schedule and capacity constraints; and Scenario 2 enhances information integration and scheduling coordination to better synchronise inbound and outbound flows and reduce idle time. Performance indicators include container dwelling time, route efficiency, resource utilisation (for example, berth and crane usage), and overall throughput. Variance-based statistical tests are applied to assess the significance of performance differences across scenarios, while sensitivity analyses examine the robustness of results to changes in key parameters such as arrival rates, resource capacities, and cargo mix, in line with simulation-based analyses of cross-docking and logistics systems (Briesemeister & Novaes, 2017; Gallo et al., 2022; Rostami, Darestani, & Movassaghi, 2022).

3.4. Validation

Model validation is conducted using a combination of conceptual, structural, and output-oriented approaches. Conceptual and structural validity are assessed through expert judgement from five domain experts, comprising academics and practitioners in port and logistics management, who review the model structure, assumptions, and process flows. Their assessments are quantified using Aiken's V to evaluate the content validity of key model components and to identify elements requiring refinement (Aiken, 1985). Behavioural validation is performed by comparing simulation outputs for the baseline scenario with available historical data and performance indicators from Batu Ampar and comparable ports, focusing on metrics such as average dwelling time, berth utilisation, and throughput levels, to ensure that the model reproduces realistic system behaviour within acceptable error range. Together, these steps provide confidence that the model is both conceptually sound and empirically credible, and therefore suitable for use in scenario and policy analysis.

Table 1 summarises the content validity results obtained from the Aiken's V analysis. Overall, 22 out of 26 indicators (84.62%) met the validity threshold, while four indicators related mainly to safety, social equity, and long-term partnerships did not. These findings suggest that the model is robust with respect to its core logistical and economic dimensions, while also highlighting opportunities for future extensions that incorporate social and partnership aspects more explicitly.

Table 1: Summary of Content Validity Results for Model Indicators (Aiken's V)

Level	Number of indicators	Valid (V ≥ 0.8)	Not valid	Examples of valid indicators	Examples of indicators below cut-off
Strategic	8	7	1	Logistics cost, regulatory compliance, environmentally friendly mode, training level	Safety practices
Tactical	9	8	1	Capacity utilisation, perceived product value, profitability, resource utilisation, customer retention	Labour equality
Opera-tional	9	7	2	Customer satisfaction, inventory cost, land availability, wage ratio	Avoidance of child/forced labour, long-term supplier partnerships

4. Results and Discussion

4.1. Results

4.1.1. Baseline Port Performance

The baseline analysis shows that major Indonesian container ports still suffer from relatively high dwelling times compared with leading regional hubs. Table 2 summarises the average dwelling time for several key ports that support domestic and inter-island distribution. While ports such as Singapore and Shanghai typically operate with average dwelling times of about one to three days, the figures for Indonesian ports indicate ongoing congestion and process inefficiencies along the national logistics chain. Batu Ampar, with an average dwelling time slightly above three days, is therefore representative of the broader situation and provides a suitable testbed for assessing a port-centric cross-docking handling model.

Table 2: Average Dwelling Time at Selected Indonesian Ports

Port	Average dwelling time (days)
Tanjung Priok (Jakarta)	2.6–3.2
Tanjung Perak (Surabaya)	3.5
Belawan (Medan)	4.1
Makassar (Sulawesi)	3.8
Batu Ampar (Batam)	3.2–4.0
Tenau (Kupang)	5.2

4.1.2. Regional Structure of Indonesian Container Ports

Pelindo has structured its container port network into four regions to manage Indonesia's wide geographical dispersion and heterogeneous demand patterns more effectively. Table 3 summarises this regional configuration, including headquarters locations, territorial coverage, and representative container ports. Region II (Jakarta/Tanjung Priok) acts as the primary international and domestic gateway, while Regions I, III, and IV focus on inter-island redistribution and connectivity to more peripheral areas. Although this regionalisation has improved coordination and operational focus, substantial infrastructure gaps and access disparities, particularly in eastern Indonesia, continue to constrain the feasibility and performance of port-centric cross-docking solutions.

Table 3: Pelindo Regional Structure and Representative Container Ports

Region	Headquarters	Main islands covered	Representative container ports*
Region I	Medan	Sumatra and surrounding islands	Belawan, Kuala Tanjung, Dumai, Batam, Tanjung Pinang
Region II	Jakarta	Western Java, southern Sumatra, Bangka–Belitung	Tanjung Priok, Teluk Bayur, Pontianak, Panjang, Banten
Region III	Surabaya	Eastern Java, Nusa Tenggara, Bali, part of Kalimantan	Tanjung Perak, Tenau Kupang, Benoa, Gresik, Kumai
Region IV	Makassar	Sulawesi, Maluku, Papua, and the eastern archipelago	Makassar, Bitung, Sorong, Jayapura, Ambon, Merauke

Note: Stefani (2023), the full list of ports per region is available in the original dataset.

4.1.3. Simulation Results for the Cross-Docking Port Handling Model

In the baseline configuration, Batu Ampar functions as a regional cross-dock for fast-moving consumer goods (FMCG) supplied from Jakarta and Medan to four island destinations, namely Tanjungpinang, Karimun, Natuna and Anambas, with the objective of minimising total distribution time (including sailing, port handling and inter-island feeder legs). Sailing times are set at 24 hours from Jakarta and 30 hours from Medan, with an average handling time of 2 hours at Batu Ampar and full route availability (availability indicator = 1). The baseline simulation shows that the optimal distribution pattern achieves a total distribution time of about 510 hours while fully satisfying demand at all destinations. The optimisation process allocates flows to routes with the lowest total time, for example routing basic staples from Jakarta to Tanjungpinang via Batu Ampar and using Medan preferentially for longer-distance destinations when capacity and time windows permit. Overall, the results indicate that, even under current infrastructural constraints, a cross-docking-oriented handling strategy at Batu Ampar can reduce average dwelling time and better synchronise outbound flows than traditional storage-intensive port operations.

4.1.4. Variance Analysis of Handling Stages

The variance analysis shows that most handling stages in the simulated port process at Batu Ampar operate with relatively stable and consistent performance. Table 4 summarises the main statistical indicators for each stage based on 10 replications, including minimum and maximum values, mean, median, variance, coefficient of variation and skewness. Stages such as container inspection, stacking by location, container gate-out and final container checks display moderate coefficients of variation and close alignment between mean and median, indicating that processing times are generally well controlled with limited dispersion. Physical inspection of containers is particularly stable, with a very low coefficient of variation and an almost symmetric distribution, suggesting that this stage is executed in a highly standardised manner. By contrast, job order issuance and truck arrival and processing exhibit higher variability and wider ranges between minimum and maximum times, reflected in larger coefficients of variation. These results point to potential bottlenecks and operational inconsistencies that can propagate delays through the cross-docking chain. From a port-centric cross-docking perspective, these stages represent critical leverage points for process redesign and digitalisation initiatives aimed at reducing handling time variability and improving overall service reliability.

Table 4: Variance Analysis for Main Handling Stages at Batu Ampar

Handling stage	N	Min	Max	Mean	Median	Variance	Coefficient of variation (CV)	Skewness
Container inspection	10	9	16	11.60	11.00	7.60	0.24	0.84
Stacking by location	10	43	70	54.00	52.50	70.89	0.16	0.70
Physical inspection of container	10	91	105	97.60	97.50	24.04	0.05	−0.07
Job-order issuance and processing	10	90	323	254.60	269.00	5,118.71	0.28	−1.55
Truck arrival and processing	10	600	1,800	1,182.00	1,080.00	209,640.00	0.39	0.19
Container gate-out	10	19	36	26.10	26.00	27.88	0.20	0.44
Final container check before exit	10	19	36	26.10	26.00	27.88	0.20	0.44

4.1.5. Model Validation with Experts

Content and structural validity of the handling model were assessed through expert judgement from five specialists in port and logistics management, comprising senior port practitioners, a dean of engineering, a supply chain management researcher, a supply chain general manager, and a transshipment supervisor, each with 10 to 25 years of experience. A total of 26 indicators across strategic, tactical, and operational levels were evaluated using Aiken's V; overall, 22 of the 26 indicators (84.62%) met the validity threshold, while four indicators (15.38%) were judged not valid for inclusion in the current model. At the strategic level, indicators such as logistics cost, regulatory compliance, environmentally friendly mode selection, and training level achieved perfect validity (V=1.00), whereas safety practices scored below the cut-off (V=0.67), indicating that occupational safety aspects are not yet sufficiently embedded in the current model configuration. At the tactical level, indicators related to capacity utilisation, perceived product value, profitability, resource utilisation, and customer retention were fully valid (V=1.00), while labour equality (V=0.60) fell below the acceptable range, reflecting the absence of explicit social equity considerations in the model design. At the operational level, customer satisfaction, inventory cost, land availability, and wage ratio were all valid ($V \geq 0.87$), whereas indicators related to avoidance of child or forced labour and long-term supplier partnerships scored low (V=0.60 to 0.67), suggesting that social and partnership dimensions are not yet captured in the current simulation. Taken together, these results indicate that the model is robust and valid with respect to its core logistical and economic dimensions, while at the same time highlighting opportunities for future extensions that incorporate safety, social, and partnership aspects more explicitly.

4.1.6. Sensitivity Analysis

The sensitivity analysis examines how changes in key cost (or time) coefficients affect the optimal allocation of FMCG flows from Jakarta and Medan to the four island destinations. Table 5 presents an extract of the sensitivity report for selected decision variables. For all active allocation variables, the reduced cost is zero and the allowable increase is extremely large, indicating that the current allocation pattern remains optimal over a wide range of higher unit costs. At the same time, the allowable decrease equals the current objective coefficient, which implies that unit costs could fall to zero without altering the optimal solution.

Table 5: Sensitivity Analysis for Selected Allocation Variables

Variable (destination)	Final value (units)	Objective coefficient	Reduced cost	Allowable increase	Allowable decrease
Tanjungpinang allocation 1	180	32	0	1E+30	32
Karimun allocation	130	37	0	1E+30	37
Tanjungpinang allocation 2	120	32	0	1E+30	32
Natuna allocation	100	44	0	1E+30	44
Anambas allocation 1	90	40	0	1E+30	40
Anambas allocation 2	90	46	0	1E+30	46

4.1.7. Scenario Testing

Scenario testing was conducted to assess how the port-centric cross-docking model responds to operational disruptions and demand shocks, using three scenarios: a delay on the Medan–Batam route (Scenario 1), a demand surge for beverages in Natuna (Scenario 2), and a supply disruption for staple products from Medan (Scenario 3), with the resulting total distribution times, allocation adjustments, and key binding constraints summarised in Table 6. When the sailing time from Medan to Batam increases, total distribution time rises to about 520 hours and light, high-value flows to Anambas are reassigned to Jakarta, with the capacity of Ferry 4 becoming the critical constraint. Under a demand surge in Natuna, total distribution time reaches 570 hours and additional beverages are allocated from Jakarta and Medan, constrained by the capacity of Ferry 3. When Medan's supply for a staple product is set to zero, total distribution time is around 495 hours and staples to Karimun are rerouted from Jakarta, with Jakarta's supply and Medan's product availability emerging as the binding constraints. Overall, the results show that the model can reconfigure flows in a structured way in response to shocks, while clearly indicating which capacity and availability limits dominate system performance in each scenario.

Table 6: Scenario Results for Total Distribution Time and Active Constraints

Scenario	Total distribution time (hours)	Main allocation adjustment	Binding or active constraints
Scenario 1: Medan delay	520	Light, high-value items to Anambas reallocated to Jakarta	Capacity of Ferry 4 on the Anambas route
Scenario 2: higher demand in Natuna	570	Additional beverages to Natuna from Jakarta and Medan	Capacity of Ferry 3 on the Natuna route
Scenario 3: zero availability Medan	495	Staples to Karimun rerouted from Jakarta	Jakarta supply and Medan product availability

4.1.8. Interpretation of Results

The combined evidence from the baseline simulation, variance analysis, expert validation, sensitivity analysis, and scenario testing yields several important insights. First, the port-centric cross-docking model at Batu Ampar is able to reduce dwelling time and rationalise flows from Jakarta and Medan to multiple island destinations, while remaining behaviourally realistic and statistically stable for most handling stages. The main operational bottlenecks that appear in the results, namely job-order processing and truck arrivals, are consistent with known weaknesses in documentation and hinterland coordination and therefore constitute priority targets for process re-engineering and digitalisation. Second, capacity constraints on specific outbound ferries, particularly those serving Natuna and Anambas, emerge as critical determinants of overall system performance; increases in vessel capacity or service frequency on these routes can substantially improve flexibility and reduce total distribution time, especially under conditions of demand surge. Third, the sensitivity and scenario analyses show that the allocation structure is relatively robust to changes in costs and travel times but vulnerable to availability shocks, which reinforces the importance of multi-source supply strategies and contingency planning. Overall, the results demonstrate that implementing a cross-docking based handling model in an archipelagic context is both feasible and beneficial, provided that port handling processes, information flows, and vessel capacities are optimised jointly rather than in isolation. For policymakers and port authorities, the findings suggest that investments in handling efficiency (for example, automation and integrated information systems), targeted capacity upgrades on critical island routes, and stronger coordination with shipping lines can deliver meaningful reductions in dwelling time and significantly enhance the performance of Indonesia's inter-island logistics system.

4.2. Discussion

4.2.1. Adapting Cross Docking to Security-Intensive Port Environments

This study refines cross-docking theory by embedding the security, regulatory, and infrastructural realities of seaport operations in an archipelagic setting. Classical cross-docking research and reviews often assume that deep physical inspections at transshipment points should be minimised to preserve high flow velocity and that detailed checks are better moved downstream to the final destination, emphasising low-touch, high-throughput operations at the cross-dock (Belle et al., 2012; Buijs et al., 2016; Savchenko & Kuzmenko, 2018). In contrast, the proposed port-handling model retains a dedicated physical inspection stage because Indonesian ports operate as highly regulated gateways involving multiple stakeholders, stringent documentation, and customs controls, and are exposed to risks such as smuggling and cargo tampering (Nur et al., 2019; Gurning & Riadi, 2022). The simulation results show that, although inspection adds a relatively stable time component, cross-docking benefits can still be realised by compressing other stages such as storage and job-order management. This indicates that cross docking at seaports needs to be adapted to security-intensive environments rather than assuming fully lean inspection regimes.

4.2.2. Manual Sorting, Job Order Management, and Transitional Constraints

The findings also nuance previous insights on buffer-zone sorting and job-order management in cross-docking terminals. Prior studies show that manual sorting and poorly coordinated truck scheduling can become major bottlenecks, and highlight the need for more automated and system-supported operations to avoid delays and errors (Belle et al., 2012; Vahdani & Zandieh, 2010; Wisittipanich et al., 2019; Coindreau et al., 2021; Gallo et al., 2022). The Batu Ampar case confirms that sorting and job-order issuance are among the most variable stages, as reflected in higher coefficients of variation and wider time ranges. However, full automation is not yet feasible given heterogeneous infrastructure and investment constraints across Indonesian ports (Nur et al., 2019; Pamadi & Sari, 2022). The model therefore treats manual sorting and dynamic job-order issuance as necessary transitional mechanisms and quantifies their time impact through separate components for schedule-related, route-related, and storage-related time. This provides a basis for future studies to evaluate the incremental benefits of progressive automation instead of assuming technologically advanced facilities as a starting point. In practical terms, the results suggest that process standardisation, digitalisation of documentation, and better coordination with trucking companies and inland transport can already reduce variability in these stages even before full automation is implemented (Nurprihatin et al., 2021; Gurning & Riadi, 2022; Nugroho et al., 2024).

4.2.3. Integration of Material, Information, and Financial Flows

A further contribution concerns the explicit integration of material, information, and financial flows at the port level. Earlier cross-docking studies frequently mention information systems only as supportive recommendations rather than as core design elements (Belle et al., 2012; Nurprihatin et al., 2021). In this model, documentation, tracking, delivery orders, port tariffs, and delay-related costs are embedded in the handling stages and linked to time components. This integrated view aligns port cross docking with contemporary flow-integration concepts in logistics and enables richer analysis of trade-offs between time, cost, and service reliability in archipelagic networks. The simulation results suggest that improvements in information quality and real-time coordination can offset some of the structural rigidity of fixed sailing schedules by allowing more responsive reallocation of flows between origin ports. In an archipelagic context, where sailing times and weather conditions are inherently uncertain, treating information and financial flows as integral parts of the handling process rather than as add-ons is therefore essential for achieving reliable cross docking performance.

Beyond these micro-level refinements, the model also connects cross docking to broader debates on supply chain resilience and port-centric logistics in volatile environments. By explicitly representing how security procedures, manual handling, and information quality interact with time components at the port node, the study complements network-level views of disruption propagation and recovery in maritime supply chains. The port-handling model shows that seaports in archipelagic systems act simultaneously as flow accelerators and potential delay amplifiers, depending on how inspection, sorting, and job-order management are configured. In theoretical terms, this positions port-centric cross docking as a meso-level mechanism that links global shipping schedules with local distribution processes, providing a structured way to analyse how operational design choices at terminals influence overall lead times, service reliability, and the capacity of multi-island logistics networks to absorb shocks.

4.2.4. Case Study Insights and Managerial Implications

The Batu Ampar case illustrates how a port-centric cross docking hub can support multi-island distribution of fast-moving consumer goods from Jakarta and Medan to downstream islands such as Tanjungpinang, Karimun, Natuna, and Anambas. Even under fixed sailing schedules, prioritising direct transfers from vessel to outbound transport, limiting storage time, and synchronising handling with outbound ferry capacity result in shorter total distribution times, particularly for time-sensitive products such as medicines and beverages. For port managers, the decomposition of total time into schedule-related, route-related, and storage-related components provides a diagnostic tool for identifying leverage points along the handling chain. The scenario analysis shows that investments in outbound capacity and handling efficiency at Batu Ampar yield greater performance gains than simply expanding storage, suggesting that ports in archipelagic networks should be developed as time-based cross docking hubs rather than storage-oriented terminals. These insights provide an empirical foundation for port authorities and policymakers to treat cross docking-oriented handling not as a theoretical abstraction but as a concrete reconfiguration of existing processes at ports like Batu Ampar, aligned with broader initiatives such as the Tol Laut programme and port digitalisation under the Indonesia National Single Window.

5. Conclusions

This study develops and evaluates a port-handling model to support cross docking in the Indonesian archipelago. By integrating a multi-level conceptual framework (strategic, tactical, and operational) with a discrete-event simulation, the research demonstrates that port handling performance can be significantly improved even under fixed maritime schedules and infrastructure constraints. The Batu Ampar case confirms that a port-centric cross docking configuration can reduce dwelling time, shorten total distribution lead time, and enhance utilisation of key resources such as berths, cranes, yards, and outbound ferries.

The model explicitly decomposes total distribution time into schedule-related, route-related, and storage-related components, providing a transparent basis for diagnosing bottlenecks and targeting improvement. Simulation experiments show that prioritising direct transfer from vessel to outbound transport, limiting storage time to cross docking windows, and synchronising handling with vessel and ferry schedules are effective strategies for accelerating flows of fast-moving consumer goods from Jakarta and Medan to surrounding islands. Sensitivity and scenario analysis further reveal that outbound ferry capacity, handling time at Batu Ampar, and supply availability at origin ports are critical determinants of overall system performance.

A key finding is that cross docking benefits at sea ports are highly dependent on information quality and real-time coordination. When estimated times of arrival, weather conditions, and demand variations are available and integrated through port information systems, Batu Ampar can operate as an adaptive hub that reallocates flows, absorbs schedule disruptions, and maintains service levels to island destinations such as Tanjungpinang, Karimun, Natuna, and Anambas. Conversely, in the absence of reliable data and synchronised job order management, handling variability and congestion rapidly erode potential time savings.

The study also shows that the proposed handling model is transferable to other major Indonesian ports with similar functional roles and operational structures. Because the model is modular and relies on standardised steps such as inspection, yard allocation, job order processing, and gate-out, it can be calibrated for ports like Belawan, Makassar, Tanjung Perak, and Tanjung Priok by adjusting local parameters without altering the underlying logic. In this way, the port-centric cross docking framework supports the broader objectives of the national maritime connectivity agenda and Tol Laut programme.

In summary, the findings indicate that port handling is not merely a static support function, but a strategic lever for improving archipelagic distribution performance. A carefully designed cross docking model, underpinned by discrete-event simulation, real-time information systems, and targeted capacity enhancements, can transform ports such as Batu Ampar into responsive distribution hubs that reduce dwelling time, enhance route efficiency, and raise the overall reliability of island logistics networks.

5.1. Theoretical and Practical Contributions

Theoretically, this study advances cross docking and port logistics research by adapting concepts that were predominantly developed for land based, deterministic networks to a maritime, archipelagic context characterised by uncertainty. The model explicitly represents travel and handling times as stochastic components and evaluates their combined effects through sensitivity and scenario analysis. This probabilistic treatment offers a more realistic representation of island logistics than conventional deterministic formulations and clarifies how fixed yet uncertain sailing schedules, weather related disruptions, and capacity constraints interact at the port node.

The research further contributes to port logistics theory by integrating material, information, and financial flows within a single port centric cross docking framework. Handling stages are linked not only to physical operations but also to documentation, tracking, tariffs, and delay related costs, enabling a richer analysis of time and cost trade offs. Information systems such as warehouse and transport management systems and real time tracking are embedded as structural elements rather than auxiliary recommendations, underscoring their central role in coordinating cross docking operations at seaports. This aligns port handling research with contemporary views on digital supply chain integration and smart logistics.

Practically, the study provides actionable guidance for port authorities, terminal operators, and policymakers seeking to enhance distribution performance in archipelagic settings. For port managers, the decomposition of total time into schedule related, route related, and storage related components offers a diagnostic framework for prioritising investments and process redesign. The simulation results indicate that resources should focus on outbound capacity on critical routes, reduction of handling times through process reengineering and partial automation, and deployment of integrated information systems to support job order management and real time decision making. For policymakers, the findings highlight the importance of treating ports such as Batu Ampar as dynamic cross docking hubs rather than passive storage points, and of aligning port handling practices with national initiatives such as Tol Laut and the Indonesia National Single Window.

5.2. Limitations and Avenues for Future Research

This study, like any modelling effort, has several limitations that create opportunities for further work. First, the analysis relies primarily on a single detailed case study at Batu Ampar, supported by expert judgement and port specific data. Although the model is designed to be generic and transferable to other ports, its empirical validation is currently confined to one operational context. Future research could replicate and extend the model in different types of ports, such as larger transshipment hubs, smaller feeder terminals, or specialised cargo facilities, to test its robustness across diverse configurations and governance structures.

Second, the simulation experiments focus on a selected set of products, routes, and scenarios, with simplified assumptions regarding demand patterns, vessel schedules, and operating policies. While this approach is suitable for exploring the main structural effects of cross docking, it may not fully capture multi period dynamics, seasonal variability, or behavioural responses from shipping lines and trucking companies. Subsequent studies could incorporate richer demand profiles, dynamic scheduling, and agent based elements to better reflect how multiple actors adapt their decisions over time. Integrating optimisation procedures with simulation, for example through simulation optimisation or digital twin concepts, would also allow more systematic exploration of alternative handling strategies and investment portfolios.

Third, the present model concentrates on time based performance indicators, such as dwelling time, total distribution lead time, and resource utilisation, without explicitly quantifying environmental and social impacts. In practice, cross docking decisions at ports also affect emissions, energy use, labour conditions, and community outcomes. Future research could extend the framework to include environmental performance metrics, for example fuel consumption and greenhouse gas emissions, and social indicators such as safety, equity, and employment quality, building on the non valid indicators identified in the content validation as potential areas for enrichment.

Finally, the study assumes progressive but still partial digitalisation of port operations, with information systems playing a central role in coordinating flows. However, digital maturity varies substantially across Indonesian ports, and the adoption of advanced technologies such as IoT, real time analytics, and integrated dashboards may face organisational, financial, and regulatory constraints. Future work could examine implementation pathways and change management strategies for deploying the proposed model in ports with different levels of digital readiness, and conduct comparative studies on digital transformation in port centric cross docking systems.

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Ethics Approval and Consent to Participate

This study did not involve human participants or animal subjects.

Conflicts of Interest

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MVP: Investigation; Data curation; Validation; Writing - review and editing.
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Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declaration of Generative AI and AI-assisted Technologies in the Writing Process

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