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Determining the International Hub Port on Sumatra Island Using the Integration of Geographic Information System and Analytical Hierarchy Process Methods

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ABSTRACT

Indonesia's maritime trade development heavily depends on the effective utilization of its port infrastructure, particularly in Sumatra, which is strategically located along the Malacca Strait and near major ASEAN markets. However, trade and logistics activities remain concentrated in Java, creating regional imbalances and leaving western Indonesian ports underutilized. This study aims to identify the most strategic ports in Sumatra that can serve as international trade hubs by developing a spatially integrated, multi-criteria evaluation framework. Three main criteria, trade volume, global connectivity, and multimodal accessibility, were assessed using the Analytic Hierarchy Process (AHP) based on expert input from port management, logistics, and transport planning specialists. Geographic Information System (GIS)-based proximity analysis was applied to evaluate each port's access to roads, railways, and industrial centers, producing a Multimodal Connectivity Index integrated into the AHP model. The findings reveal that Boom Baru (Palembang), Belawan (Medan), and Batu Ampar (Batam) rank as the top-performing ports, with final scores of 0.875, 0.855, and 0.800, respectively. These ports exhibit high trade volumes and superior multimodal connectivity, with Boom Baru and Belawan achieving the highest connectivity index (2.67 out of 3.00). In contrast, Pekanbaru and Tanjung Balai Karimun scored lower due to limited infrastructure and weaker integration. The study concludes that incorporating GIS-based spatial analysis into the AHP framework reduces subjectivity in port evaluation and provides a replicable, data-driven tool for regional infrastructure prioritization. This approach contributes a novel composite index and offers strategic insights for developing Sumatra's role in Indonesia's maritime trade network.

1. Introduction

The growth of global export and import trade continues to rise, driven by economic advancement and shifting global market preferences. Countries engage in international trade for various economic and strategic reasons. In 2024, Indonesia's import value reached USD 233.66 billion, a 5.31% increase from 2023's USD 221.94 billion (Afiatno & Joyoutomo, 2024; Indrawati et al., 2024). The top five import partners were China (USD 65.38 billion), Japan (USD 10.53 billion), Australia (USD 7.32

billion), Singapore (USD 5.10 billion), and Thailand (USD 4.87 billion) (Basia et al., 2025; Yudha & Anwar, 2025).

International trade plays a critical role in global economic development (Ji et al., 2022), and exporters and importers increasingly seek efficient strategies to expand their market reach. Export transportation is fundamental in facilitating trade, ensuring smooth cross-border movement, reducing logistical complexities, and enhancing supply chain performance (Gani, 2017; Sénquiz-Díaz, 2021). Specialized service providers integrate land, sea, and air transport modes into cohesive multimodal systems, improving delivery reliability and cost-effectiveness (Li et al., 2023; Skender et al., 2016).

The integration of sea and rail transport has emerged as a sustainable and cost-efficient alternative to road transport (Burinskiene, 2022). (Abu-Aisha et al., 2024) highlighted in a systematic review that such intermodal systems reduce congestion, lower greenhouse gas emissions, and improve freight sustainability. Effective connections between ports and inland rail networks further enhance timely deliveries and environmental outcomes (Hu et al., 2019).

This study focuses on Sumatra due to its strategic geographic location and economic importance in Indonesia's international trade network (Tampubolon & Nababan, 2018; Wulandary et al., 2022). Positioned along the Malacca Strait, Sumatra offers proximity to major ASEAN economies like Singapore and Malaysia (Ansofino & Zusmelia, 2017), making it a strong candidate for an international trade hub. However, much of Indonesia's trade continues to rely on Java's ports, particularly Tanjung Priok, resulting in logistical bottlenecks for businesses in Sumatra and surrounding regions (Dwitasari et al., 2021).

This concentration on Java can be attributed to historical infrastructural investment biases, institutional inertia, and the centralization of trade policy and customs administration in Java-based governance structures. Additionally, limited multimodal connectivity and underdeveloped port facilities in Sumatra hinder its competitiveness, despite its geographic advantages (Prastyabudi et al., 2024). These systemic disparities underscore the need for decentralized infrastructure development and policy reforms that acknowledge regional trade potential beyond Java.

Developing a well-integrated international hub port in other Indonesia's main island could reduce congestion in Java, lower logistics costs, and boost Indonesia's global trade competitiveness (Lestari, 2021). Sumatra is also home to several major industrial and resource-producing regions, such as palm oil, rubber, coal, and crude oil, which are vital to Indonesia's export economy (Statistik, 2025). Industrial centers defined as regions designated for manufacturing, warehousing, and distribution thrived on robust infrastructure and transport connectivity (Das, 2012).

Among Sumatra's key ports, the Port of Kuala Tanjung in North Sumatra stands out. Strategically located near the Strait of Malacca and integrated with the Sei Mengke Special Economic Zone, this port is designed to handle significant cargo volumes, especially from the palm oil and rubber sectors (Suryana, 2020). It is expected to manage 65% of North Sumatra's total goods production and has attracted investments like Unilever's oleochemical facility (Mutia et al., 2019; Sinaga et al., 2018).

Industrial clusters, particularly in Sumatra, complement the region's port infrastructure by anchoring production and trade activities close to export gateways. Based on Alfred Marshall's agglomeration theory and Michael Porter's cluster theory, play a key role in regional economic development by enhancing productivity and innovation through co-located firms (Delgado et al., 2014). These clusters reduce transport costs, promote specialization, and strengthen linkages between firms and labor markets. In Indonesia, such clusters and industrial corridors are instrumental in promoting balanced regional growth and enhancing port connectivity (Berawi et al., 2020).

Another prominent port is Belawan Port in Medan, the busiest seaport outside Java. It serves as a key gateway for exports like rubber, palm oil, tea, and coffee. A recent partnership with DP World aims to double its capacity to 1.4 million TEUs (Juangsa & Ahmad, 2025), attracting more direct shipping lines and reducing reliance on Java-based or Singaporean transshipment hubs, thereby improving North Sumatra's global shipping integration (Donnadieu et al., 2022; Laksmana, 2020).

Indonesia’s port infrastructure plays a crucial role in national trade logistics, yet maritime activity remains highly concentrated in Java causing congestion, high logistics costs, and regional imbalance (Amin et al., 2021; Yudhistira & Sofiyandi, 2018). Meanwhile, Sumatra is strategically positioned along the Malacca Strait and rich in export commodities such as palm oil, coal, and rubber, yet its port system remains underutilized. Identifying the most strategic port hub in Sumatra is therefore essential to unlocking its trade potential, redistributing logistics flows, and enhancing Indonesia’s maritime competitiveness. A strategic port, in this context, is one that not only handles significant cargo volumes but also offers superior multimodal accessibility, infrastructure readiness, and potential for future expansion. Prior studies have applied AHP and GIS frameworks for port site selection (Ali et al., 2023; Nguyen et al., 2021), but few focus specifically on Sumatra with an integrated approach. Thus, this study fills a methodological and contextual gap by systematically evaluating and prioritizing Sumatran ports to support more balanced and sustainable regional development. A literature demonstrates how GIS-AHP integration enables robust decision-making in diverse contexts, from site-suitability analyses to port competitiveness evaluations (Lee et al., 2014).

This study addresses these gaps by using an AHP model integrated with GIS to assess the strategic potential of ports in Sumatra. It evaluates trade volumes and logistical performance using a data-driven, spatially integrated framework. Unlike traditional qualitative approaches, this research adopts Geographic Information Systems (GIS) and an Analytical Hierarchy Process (AHP) to evaluate multimodal transport efficiency, trade accessibility, and infrastructure readiness in Sumatra, addressing the need for data-driven tools in strategic port selection.

The contribution of this research is the development of a spatially integrated, AHP framework that minimizes subjectivity in port selection, offering a replicable decision-making model for optimizing Indonesia’s infrastructure and trade competitiveness. By empirically evaluating export performance across multiple Sumatran ports, our study provides actionable insight for policy formulation, investment planning, and sustainable regional development, contributing directly to the literature through an applied, export-focused port hub analysis.

2. Method

This study employs a multi-criteria decision-making approach by integrating GIS and AHP to determine the most suitable international hub port in Sumatra. The methodology consists of four main stages: data collection and preprocessing, GIS-based spatial analysis, AHP-based criteria weighting, multimodal connectivity index, and final port ranking. The integration of GIS enables an objective spatial analysis of logistics infrastructure and connectivity, while AHP provides a structured decision-making framework incorporating normalized values as the direct AHP weights.

2.1. Initial Data Collection and Preprocessing

The study utilizes open-source and official datasets to construct a comprehensive geospatial and economic dataset for port selection. Port locations and infrastructure data are sourced from OpenStreetMap (OSM), providing geographic coordinates and transportation capacity details of major ports in Sumatra. Prior to analysis, all datasets were standardized to a common coordinate reference system (WGS 84) and cleaned to remove duplicates and inconsistencies. Trade volumes were normalized to account for variations in reporting granularity across years and ports.

Trade volume data obtained from Central Bureau of Statistics (BPS) Indonesia. To ensure analytical focus and operational relevance, this study applies a filtering criterion by selecting only the top five ports in Sumatra based on cumulative export and import volumes over the 2019–2023 period. This threshold is used to reduce data complexity while retaining the most economically significant nodes in the regional logistics network. Prioritizing high-volume ports aligns with established practices in port performance and accessibility studies, where throughput volume is commonly used as a proxy for economic relevance and infrastructure demand (Notteboom & Rodrigue, 2005; Smith & Hensher, 2020).

Table 1. Sumatra Main Port's Export Volume (hundred thousand tons)

Province	Main Port	2019	2020	2021	2022	2023	Total
Sumatera Utara	Belawan Port	7944	7173	7873.3	7849	8497.1	39336.4
Sumatera Barat	Padang/ Teluk Bayur	4610.5	4272	5340.1	4150	5052,3	23424.9
Sumatera Selatan	Musi River/ Boom Baru	20506.1	18093.4	26846.7	39595.9	43851.3	148893.4
Riau	Dumai	18881.2	18497.1	18461	17707.5	18287.6	91834.4

The export and import volumes of Sumatra's main ports reveal distinct patterns of regional trade performance. Boom Baru Port in South Sumatra recorded the highest export volume over the 2019–2023 period as shown in Table 1 and Table 2, with a cumulative total of approximately 14.89 million tons, underscoring its vital role in supporting the province's robust commodity production, particularly in rubber and palm oil. It was followed by Dumai Port in Riau, which reached 9.18 million tons, and Belawan Port in North Sumatra with 3.94 million tons. The dominance of Boom Baru and Dumai in export activity aligns with the presence of large-scale industrial zones and agro-based processing facilities near these ports.

Table 2. Sumatra Main Port's Import Volume (hundred thousand tons)

Province	Main Port	2019	2020	2021	2022	2023	Total
Sumatera Utara	Belawan Port	5785.2	5337.5	5757.7	5931.7	6282.9	29095
Lampung	Tanjung Balai Karimun	1347.3	2493.1	2924	1481	3014.1	11259.5
Kepulauan Riau	Panjang	1936.2	1820.5	2064.2	1958.7	2117.3	9896.9
Kepulauan Riau	Batu Ampar	1816.1	1825.5	1733.5	2117.4	2486.2	9978.7

In contrast, import volumes show a different distribution. Belawan Port led in imports, handling approximately 2.91 million tons, indicating its significance as a distribution hub for consumer goods and industrial inputs into North Sumatra and neighboring regions. Tanjung Balai Karimun and Panjang Port also showed substantial import activity, with cumulative totals of 1.13 million and 0.99 million tons, respectively. Batu Ampar Port in the Riau Islands, while ranked lower in exports, handled nearly 1.00 million tons in imports, reflecting its integration within the Singapore-Johor-Riau economic triangle and its function as a regional feeder port. These import volumes highlight the strategic function of certain ports in supporting domestic supply chains and regional consumption centers, especially in North Sumatra and western Indonesia.

2.2. Multimodal Analysis and AHP

The multimodal connectivity analysis conducted in this study quantifies the integration of Sumatra's ports with inland transport infrastructure and adjacent industrial centers. Using ArcGIS Pro's Near tool, geodesic distances were calculated from each major port to the nearest road, railway, and designated industrial zone. These distances were then classified into accessibility scores on a scale from 1 to 3, where a score of 3 represents proximity within a highly accessible threshold and 1 denotes limited accessibility. These thresholds were derived from relevant transport planning literature (Cullinane & Wang, 2009; J. Guo et al., 2022; Jarumaneeroj et al., 2023; Papaioannou & Wagner, 2019) and refined through expert consultation. A score of 2 was assigned for moderately accessible distances that fall between limited and high accessibility thresholds (with 6–15 km for roads, 6–10 km for rail, and 31–60 km for industrial zones).

The AHP method was implemented through six steps: selecting evaluation criteria based on literature and expert input; conducting pairwise comparisons with seven experts using Satays' 1–9 scale; checking consistency ratios ($CR \leq 0.1$); aggregating weights using the geometric mean method;

normalizing port performance scores with min–max scaling; and calculating final scores using a weighted sum model. The AHP hierarchy used in this study is structured into three levels. At the top level is the overall goal, which is to identify the most strategic port hub in Sumatra. The second level consists of three evaluation criteria: trade volume, global connectivity, and multimodal access. The third level includes the port alternatives evaluated. This hierarchical structure guided the expert pairwise comparison process and was used to derive final port rankings using the AHP method.

To integrate multimodal with the AHP approach, the accessibility scores were normalized and used as input for the AHP pairwise comparison matrix, allowing them to influence the overall ranking of port suitability alongside other strategic criteria. The resulting scores from the multimodal analysis were thus not only used as descriptive metrics but also operationalized as part of the AHP evaluation framework to ensure alignment between spatial connectivity and decision prioritization.

The criteria selected for AHP evaluation are based on strategic logistics considerations and the functionality of each port within both national and international trade contexts. The selection of the three evaluation criteria (trade volume, global connectivity, and multimodal connectivity) was informed by both academic literature and expert consultation. The selected criteria reflect key strategic logistics considerations. Trade volume indicates operational scale (Notteboom & Rodrigue, 2005), global connectivity reflects integration into shipping networks (Jarumaneeroj et al., 2023), and multimodal access captures inland linkages vital for port competitiveness (Bocarejo S. & Oviedo H., 2012). Trade volume refers to the total amount of cargo handled by a port, including both imports and exports. This criterion reflects the operational scale and economic importance of the port within the supply chain. A highly connected port enables better access to global markets. Multimodal access evaluates the availability and quality of supporting transportation infrastructure, including road, rail, and sea transport. This aspect is essential for seamless cargo movement from origin to destination.

To validate the applicability of these criteria in the Indonesian context, structured interviews and consultations were conducted with six experts. The experts confirmed that the selected criteria align with Indonesia's national port development priorities as outlined in the National Port Master Plan and the RPJMN 2020–2024 (National Mid-Term Development Plan), particularly in terms of boosting export competitiveness and improving inland logistics integration.

To implement the AHP method, a structured questionnaire was distributed to six respondents including two transport planning experts, two port management representatives, and two logistics scholars. These experts were asked to perform pairwise comparisons of the selected criteria using Saaty's 1–9 scale where 1 denotes equal importance and 9 denotes extreme importance of one criterion over another. The questionnaire also included brief operational definitions of each criterion to ensure consistent understanding across respondents. Responses were reviewed for consistency, and individual consistency ratios (CR) were calculated. All responses with CR ≤ 0.10 were included in the aggregation process. The final pairwise comparison matrices were synthesized using the geometric mean method to derive the relative weights of each criterion.

The aggregated weights derived from these expert inputs were then combined with standardized performance scores of each port using the AHP method. This process allowed the integration of both expert-based priority weighting and data-driven evaluation, enhancing the robustness and transparency of the final port rankings.

2.3. GIS-Based Spatial Analysis

The GIS-based spatial analysis is conducted to evaluate the accessibility and connectivity of ports in Sumatra by mapping essential logistics infrastructure using ArcGIS. Several spatial layers are overlaid to provide a comprehensive view of port accessibility in Sopha et al., (2018), including port locations, which are plotted based on geographic coordinates, industrial areas and economic centers Wisnicki et al., (2021), which are mapped to assess their proximity to ports, multimodal transport networks Kotikov (2017), which integrate road, rail, and river connectivity to evaluate hinterland accessibility, and international shipping lanes Valjarevic et al., (2021), which highlight major global maritime routes to determine trade accessibility.

The analysis utilized several key datasets, including major ports in Sumatra such as Belawan Port, Dumai, Panjang, Padang, and Palembang. It also incorporated industrial centers like Sei Mangkei, KI Tanjung Buton, KI Tenayan, Medan, Padang Industrial Park, Palembang, and Batam. In addition to these point datasets, spatial infrastructure layers were included, specifically the road and railway networks derived from OpenStreetMap. Industrial centers were selected based on their recognition in national spatial plans (RTRWN, RPJMN), economic zone policies (SEZ/KEK), and actual clustering of export-oriented industries such as palm oil, rubber, and coal.

To ensure accuracy and consistency in distance calculations, all datasets were projected to the WGS 1984 UTM Zone 47S or 48S coordinate systems, depending on their geographical coverage. The spatial relationship between ports and infrastructure was then assessed using the Near analysis tool in ArcGIS Pro. This tool calculated the closest distance from each port to the nearest road, railway, and industrial center. These distances were then classified into categorical scores ranging from 1 to 3, based on proximity thresholds established in the study Cullinane & Wang (2009) and further refined through expert consultation. The scoring criteria reflect typical operational access ranges found in multimodal logistics and port accessibility studies, and were validated by transportation planners and logistics specialists consulted during this research. Finally, the individual mode scores were averaged to derive a comprehensive multimodal connectivity Index for each port as shown in Fig. 1.

Fig. 1. Digitalized Map of Sumatra's Toll Road, Railway, Main Ports, Industrial Center, and Main Cities

Following this, a proximity analysis is conducted to quantify each port's accessibility relative to economic hubs. Using the Near Analysis tool in ArcGIS, the Euclidean distance from each port is computed in relation to major industrial zones such as Medan, Padang, and Palembang, major cities and logistics centers to evaluate hinterland reach, and global shipping lanes to determine direct access to international markets. The results of this analysis shown in Fig. 2, provide a ranked measure of each port's spatial advantage in trade facilitation, offering insights into which locations are best positioned for international hub development.

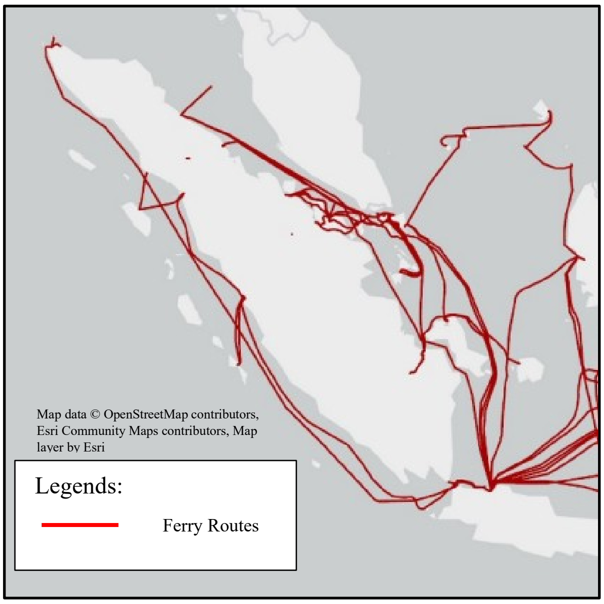

Fig. 2. Digitalized Map of Sumatra's Ferry Routes.

3. Results and Discussion

3.1. Multimodal Analysis and AHP Results

To determine the multimodal connectivity index, each port was evaluated based on its distance to three key infrastructures: major roads, railway lines, and designated industrial zones. For each component, a discrete score ranging from 1 to 3 was assigned based on threshold distances. For road access, ports located within 3 kilometers were given a score of 3, those within 3 to 5 kilometers scored 2, and distances greater than 5 kilometers scored 1. Similarly, for rail access, distances of 5 kilometers or less scored 3, 6 to 20 kilometers scored 2, and more than 20 kilometers scored 1. For industrial zone proximity, scores of 3, 2, and 1 were assigned to distances of ≤10 kilometers, 11–30 kilometers, and >30 kilometers, respectively.

These thresholds were adapted from regional transportation planning standards and refined through expert validation. The final multimodal connectivity index was calculated as the arithmetic mean of the three sub-scores, using Eq. (1).

$$Multimodal\ Index = \frac{S_{road} + S_{rail} + S_{industrial}}{3} \tag{1}$$

To ensure academic rigor, the component scoring method aligns with accessibility frameworks proposed in the literature, such as benchmarking proximity-based accessibility in OECD/ITF (Papaioannou et al., 2019), which advocates structured distance thresholds and averaging across multiple modes to assess integration.

The multimodal connectivity analysis results, as shown in Table 3, indicate that Boom Baru Port (Palembang), Belawan Port (Medan), and Panjang Port achieved the highest Multimodal Connectivity Index of 3.00. Boom Baru is located just 2.1 kilometers from a major road, 0.8 kilometers from the nearest railway, and 5.2 kilometers from the Palembang industrial estate, reflecting excellent integration. Belawan Port is equally well connected, being within 3 kilometers of a major road, 2 kilometers of a railway line, and 20.3 kilometers from the Sei Mangkei SEZ. Panjang Port also demonstrated optimal connectivity with all three infrastructures within preferred distance thresholds.

Dumai Port followed with a strong index of 2.67, reflecting excellent road and industrial zone access but slightly less optimal rail distance. Batu Ampar Port (Batam) scored 2.33, benefiting from strong road and industrial zone access, but its lack of rail connectivity limited its index. Similarly, Teluk Bayur Port (Padang) also scored 2.33, with moderate proximity to all three infrastructures. In contrast, Tanjung Balai Karimun scored 1.67, reflecting moderate road access but limited integration with rail and industrial zones. Pekanbaru Port recorded the lowest score of 1.33, due to relative isolation from all three infrastructures, especially rail and industrial centers located beyond optimal thresholds.

Table 3. Multimodal Connectivity Index

Port	Distance to Road (km)	Road Score	Distance to Rail (km)	Rail Score	Distance to Industrial Zone (km)	Industrial Score	Multimodal Index
Boom Baru (Palembang)	2,1	3	0,8	3	5,2	3	3
Belawan Port (Medan)	2,5	3	1,9	3	20,3	3	3
Batu Ampar (Batam)	1,8	3	30	1	18,4	3	2,33
Tanjung Balai Karimun	4,2	2	35	1	25,6	2	1,67
Pekanbaru	6,5	2	33	1	40	1	1,33
Dumai	3	3	5,2	2	19	3	2,67
Panjang	2,4	3	1,5	3	15	3	3
Teluk Bayur (Padang)	4,5	2	12	2	8,2	3	2,33

The pairwise comparison matrix for AHP analysis is constructed using the Saaty scale, which allows decision makers to express the relative importance between two criteria in a structured way. To obtain these judgments, a structured questionnaire was distributed to six experts, including port managements, transportation planners, and logistics scholars. Each respondent independently completed pairwise comparisons among the selected criteria which trade volume, global connectivity, and multimodal access using Saaty's 1–9 scale. Consistency ratios (CR) were calculated for each response, and only those with CR ≤ 0.10 were retained for aggregation. Intermediate values (2, 4, 6, 8) can be used for compromise between the preferences. The reciprocal of each value is used when the comparison is in the opposite direction (e.g., if criterion A is strongly more important than criterion B, then A vs B = 5 and B vs A = 1/5).

The relative importance of each criterion was evaluated using the Saaty scale (1-9). The resulting pairwise comparison matrix is shown in Table 4.

Table 4. Relative Importance Criterion Pairwise Comparison Matrix

	Trade Volume	Global Connectivity	Multimodal Access
Trade Volume	1	3	5
Global Connectivity	1/3	1	3
Multimodal Access	1/5	1/3	1

The normalized matrix was constructed by dividing each entry in the pairwise comparison matrix by the sum of its column, followed by calculating the average of each row to obtain the final weights. The results, shown in Table 5, indicate that trade volume (0.634) was considered the most important criterion in port evaluation, followed by global connectivity (0.260), and multimodal access (0.106).

Each port was evaluated on a normalized scale (0 to 1) for all three criteria based on trade volume, global connectivity, and multimodal access. The normalization process was applied to ensure comparability across metrics with different units. For trade volume, annual throughput data (in metric tons) was sourced from official BPS (Badan Pusat Statistik) port statistics and normalized using min–max scaling. Global connectivity was assessed based on the number of direct international shipping routes and the presence of major shipping lines, using data obtained from port authority reports and validated through infrastructure attributes available in OpenStreetMap. Multimodal access was derived from the GIS-based scoring index described previously, where road, rail, and industrial zone proximity scores were averaged. The weighted scores were then calculated using the AHP-derived weights. The final score for each port was determined using the modification AHP formula of Saaty (1980).

Table 5. Normalized AHP Weight

Criterion	AHP Weight
Trade Volume	0.634
Global Connectivity	0.260
Multimodal Access	0.106

$$\sum_{i=1}^{n} \omega_{\mathrm{i}} \cdot x_{ij} \tag{2}$$

Table 6, presents the final AHP scores calculated for each evaluated port in Sumatra. These scores were calculated using Eq. (2). The input data for port performance were based on operational statistics, spatial connectivity maps, and publicly available logistics reports. In this study, the term 'normalized performance score' x_{ij} refers to the rescaled value of each port's performance on a given criterion to ensure comparability across units and scales. For the Multimodal access criterion, this score is derived from the multimodal accessibility index, based on geodesic distances to road, rail, and industrial centers.

Table 6. Port Score using AHP

Port	Trade Volume (x_{1j})	Multimodal Access (x_{2j})	Expansion Potential (x_{3j})	Final Score
Boom Baru (Palembang)	0.95	0.85	0.80	0.875
Belawan Port (Medan)	0.90	0.87	0.75	0.855
Batu Ampar (Batam)	0.85	0.90	0.60	0.800
Dumai (Riau)	0.70	0.80	0.60	0.743
Panjang (Lampung)	0.68	0.75	0.65	0.742
Teluk Bayur (Padang)	0.65	0.70	0.60	0.709
Tanjung Balai Karimun	0.60	0.65	0.55	0.681
Pekanbaru	0.55	0.60	0.50	0.557

Among the evaluated ports shown in Table 6, Boom Baru (Palembang) achieved the highest score of 0.875, followed closely by Belawan Port (Medan) with 0.855. These results highlight their superior logistics performance across all three criteria, particularly in trade volume and multimodal connectivity. Batu Ampar (Batam) also emerged as a strong contender due to its global connectivity and future expansion potential. On the other hand, ports like Pekanbaru and Tanjung Balai Karimun scored lower, indicating areas where infrastructure and strategic investment may be needed.

3.2. GIS

The geodesic distance matrix between ports and industrial centers showed that Belawan Port has high proximity to Sei Mangkei and Medan, while Palembang is close to its namesake industrial hub.

Padang and Port Dumai showed moderate-to-low industrial proximity. These relationships were tabulated in the Table 7.

Table 7. Port to Industrial Center Matrix of Distance (km)

	Sei Mangkei	KI Tanjung Buton	KI Tenayan	Padang Industrial Park	Medan	Palembang	Batam
Belawan Port (Medan)	20.2	494.85	481.02	553.29	20.2	1008.2	662.53
Dumai (Riau)	374.15	114.24	130.84	313.36	374.15	634.29	293.92
Panjang (Lampung)	1243.89	785.26	781.67	743.96	1243.89	279.68	742.8
Boom Baru (Palembang)	538.97	269.71	204.9	4.93	538.97	534.82	466.7
Teluk Bayur (Padang)	89.81	399.03	389.03	481.16	89.81	915.04	565.57
Batu Ampar (Batam)	1210	980	950	1200	1210	1560	3.9
Tanjung Balai Karimun	380	245	220	350	380	620	54.5
Pekanbaru	318.6	81.9	139	403.4	318.6	915	299.7

Each port's proximity to road and rail networks was also evaluated in Table 7. All eight ports exhibited strong road connectivity, but rail access varied significantly. Belawan Port and Palembang performed best in all three criteria, aligning with their high AHP suitability scores.

The spatial proximity analysis between ports in Sumatra and their nearest industrial centers provides valuable insight into potential logistical linkages. For instance, the analysis indicates that Belawan Port, located at approximately 3.77°N and 98.68°E, is closest to Sei Mangkei SEZ, with a separation of approximately 0.18 decimal degrees, or roughly 20 kilometers. This close proximity supports Belawan's role as a key export hub for palm oil and rubber derivatives processed in Sei Mangkei. Similarly, Dumai Port, situated in Riau, appears to be nearest to either KI Tanjung Buton or KI Tenayan, at an approximate distance of 1.03° or around 115 kilometers. While this distance is relatively farther compared to Belawan or Sei Mangkei, it still positions Dumai within a feasible logistics corridor for inland-industrial access.

Meanwhile, Panjang Port, shows a more distant relationship with its nearest industrial center which possibly Padang Industrial Park or Batam with a distance exceeding 2.5°, or approximately 280 kilometers. This greater distance may indicate limited direct industrial integration and could suggest the need for improved multimodal infrastructure to enhance accessibility. Another noteworthy observation comes from the entry representing Padang Port, which is shown to be approximately 0.45° (about 50 kilometers) from Sei Mangkei, suggesting a moderate level of industrial proximity. Overall, the spatial results reinforce the idea that ports like Belawan and Palembang benefit from their nearness to major industrial zones, a factor that enhances their multimodal connectivity and strengthens their strategic positioning in the Sumatra logistics network.

The GIS-based proximity analysis aligns closely with the AHP results, reinforcing the robustness of the evaluation framework. Ports like Belawan and Palembang, which ranked highly in the AHP model in Table 6, are also well-positioned near major industrial zones and exhibit strong multimodal connectivity Table 7. Similarly, Dumai and Batu Ampar scored well in both the AHP and the Multimodal Connectivity Index Table 3, confirming the consistency between spatial accessibility and expert judgment. In contrast, ports such as Panjang and Pekanbaru, which are farther from key infrastructure, received lower AHP scores, highlighting the importance of spatial integration in port performance.

The spatial proximity data in Table 7, served as the empirical input for one of the AHP evaluation criteria which is multimodal access demonstrating the integration of GIS results into the decision-making framework. Ports that are closer to industrial zones and transport nodes received higher proximity scores, which directly influenced their final AHP ranking. This reflects how the GIS analysis is not a separate layer but a critical, quantified contributor to the overall AHP-based port prioritization process.

The final AHP scores provide a structured evaluation of the strategic value of major ports in Sumatra. Boom Baru (Palembang) and Belawan Port (Medan) emerged as the top-performing ports, with final scores of 0.875 and 0.855 respectively. These ports demonstrated high trade volume, strong global connectivity, and superior multimodal access, particularly via well-developed road and rail networks. Their proximity to major road networks (2.1 kilometers and 2.5 kilometers), rail infrastructure (0.8 kilometers and 1.9 kilometers), and nearby industrial zones (5.2 kilometers and 20.3 kilometers) reinforces their logistical efficiency and supply chain performance. Both ports are also closely linked to strategic industrial estates Palembang for Boom Baru and Sei Mangkei for Belawan enhancing their value as multimodal gateways. Panjang Port also demonstrated high connectivity with an index of 3.00, supported by strong integration across all three access dimensions. While its AHP score was not explicitly detailed, its high multimodal connectivity suggests significant potential for optimized freight handling and inland distribution (Kusumawardani & Widyatmoko, 2024; Putri et al., 2024).

Batu Ampar (Batam) secured an AHP score of 0.800, driven by excellent global connectivity and promising expansion potential through its strategic location within the Indonesia-Malaysia-Singapore Growth Triangle. However, its multimodal index of 2.33 reflects a notable weakness in rail access (30 kilometers), which limits its integration compared to top-performing ports. Similarly, Dumai Port, with a multimodal index of 2.67, benefits from road and industrial proximity but shows weaker rail integration.

Teluk Bayur (Padang) scored 2.33 on the multimodal index, reflecting moderate proximity to roads and industrial zones but limited railway access. Its spatial proximity, approximately 50 kilometers from Sei Mangkei, positions it as a secondary hub with potential if supported by targeted rail infrastructure development. At the lower end of the performance spectrum, Tanjung Balai Karimun and Pekanbaru received final AHP scores of 0.681 and 0.557, respectively. These scores reflect limited multimodal access, particularly poor rail connectivity and significant distance from key industrial zones. The multimodal indices of 1.67 and 1.33, respectively, reinforce the lack of logistical integration, which reduces their attractiveness for export-oriented development despite underlying resource potential.

The AHP weight analysis underscored the dominant influence of trade volume (0.497) and global connectivity (0.246) in determining port performance, with multimodal access (0.124) serving as a key enabler of inland and cross-regional transport integration. Ports such as Boom Baru and Belawan, which scored highly in all three categories, benefit from close proximity to major industrial centers (e.g., Palembang, Sei Mangkei, and Medan) and established connections to both rail and road networks, enabling more efficient cargo flow and supply chain performance. Conversely, ports with limited multimodal integration, such as Pekanbaru and Tanjung Balai Karimun, remain underutilized despite their export potential.

The GIS–AHP integration in this study aligns with findings from GIS applications in maritime ports, which highlight the value of geospatial proximity analysis in port evaluation frameworks (Isbaex et al., 2025). Such studies emphasize the use of spatial tools to support decision-making in port management (Chou, 2010). Studies from (Chou, 2010) and (Akbari et al., 2017) showed the spatial proximity patterns from GIS analysis directly reinforce the AHP results which is high-performing ports like Boom Baru and Belawan are also those closest to infrastructure hubs, demonstrating a clear relationship between accessibility and strategic ranking. In addition, port competitiveness models from (Wan et al., 2022) found that infrastructure and intermodal service integration significantly enhance port competitiveness, particularly regarding cargo throughput and hinterland connectivity.

The multimodal connectivity index further supported these findings by quantifying the degree of transport integration at each port. Boom Baru and Belawan both achieved the highest scores (2.67 out of 3.00), owing to their proximity to rail lines (0.8 kilometers and 1.9 kilometers respectively), short distances to industrial zones (5.2 kilometers and 20.3 kilometers), and well-connected road networks (under 3 kilometers). Batu Ampar followed with a score of 2.33, while Dumai and Panjang recorded scores of 2.67 and 3.00 respectively, highlighting their comparable accessibility. Lower scores were observed at ports like Pekanbaru (1.33) and Tanjung Balai Karimun (1.67), where access to rail and industrial facilities remains limited. These quantified connectivity metrics reinforce the spatial patterns revealed in GIS visualizations and further validate the AHP model rankings.

These findings indicate that logistics infrastructure development in Sumatra should prioritize ports with demonstrated strengths in trade throughput, connectivity, and multimodal integration. Investments in handling capacity, digital systems, and intermodal terminals in ports like Boom Baru and Belawan could consolidate Sumatra's position as a regional logistics powerhouse. This findings align with broader evidence that building transshipment and intermodal terminals is essential to enhance regional trade connectivity, improve supply chain efficiency, and drive economic growth (Herdian et al., 2025). (T. Guo et al., 2023) also presents an integrated model to assess modal-shift policies and optimize transport mixes, including intermodal terminals and connectivity at ports. Meanwhile, ports with moderate AHP scores but strong growth potential such as Batu Ampar and Dumai warrant strategic infrastructure upgrades and policy support to unlock their full capacity. Lower-performing ports like Pekanbaru require targeted interventions to address connectivity limitations and encourage cargo clustering around industrial activity.

The GIS-based spatial analysis provides strong validation for the port rankings generated through the AHP evaluation. Ports that received high AHP scores, such as Boom Baru (Palembang) and Belawan (Medan), also demonstrated strong spatial integration, as evidenced by their close proximity to key infrastructure components. Boom Baru, for instance, is located within 5 km of road, rail, and industrial zones, earning a perfect multimodal connectivity index score of 3.00. Similarly, Belawan scored 2.67, reflecting its strategic location near the Sei Mangkei industrial area and its integration with multiple transport modes. In contrast, lower-ranked ports like Pekanbaru and Tanjung Balai Karimun, which scored below 0.60 in the AHP model, are located further from industrial clusters and have limited rail access, factors reflected in their low connectivity indices (1.33 and 1.67, respectively). This spatial pattern reinforces the reliability of the AHP results by showing a consistent alignment between expert-assigned scores and objectively measured multimodal accessibility through GIS.

While the AHP model offers a robust and structured methodology, it is based on a static set of criteria and expert-derived judgments (Benítez et al., 2011). To enhance future evaluations, dynamic data such as vessel call frequency, terminal performance, and logistics cost indicators should be incorporated. Furthermore, integrating GIS with stakeholder surveys and real-time analytics will offer a more comprehensive and adaptive assessment framework, supporting spatially informed decision-making for Indonesia’s long-term maritime and logistics development strategy.

4. Conclusion

TThis study identified the most strategic port hubs in Sumatra through a multi-criteria decision-making framework integrating economic indicators, trade volumes, and infrastructure connectivity using GIS and AHP methods. The combined analysis revealed Boom Baru (Palembang) and Belawan (Medan) as the most competitive ports, supported by high trade activity, robust multimodal accessibility, and strong integration with industrial zones. These findings highlight the spatial disparities within Sumatra’s port network and emphasize the need for targeted infrastructure investment to optimize regional logistics performance. The integration of GIS-based spatial analysis into the AHP model proved effective in reducing subjectivity and enhancing the validity of port evaluations, offering a replicable tool for infrastructure prioritization and policy formulation. Future studies are encouraged to incorporate dynamic operational data, such as vessel calls, logistics performance, and cost indicators, as well as environmental and socio-economic dimensions to strengthen the model's comprehensiveness and applicability in supporting sustainable maritime development.

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References

Abu-Aisha, T., Audy, J.-F., & Ouhimmou, M. (2024). Toward an efficient sea-rail intermodal transportation system: a systematic literature review. *Journal of Shipping and Trade*, *9*(1), 23. https://doi.org/10.1186/s41072-024-00182-z

Afiatno, B. E., & Joyoutomo, K. D. (2024). The economic impact of dry port investment in Indonesia: A case study of Bangil, Pasuruan District, East Java Province. In *Cleaner Logistics and Supply Chain*. Elsevier. https://www.sciencedirect.com/science/article/pii/S2772390924000416

Akbari, N., Irawan, C. A., Jones, D. F., & Menachof, D. (2017). A multi-criteria port suitability assessment for developments in the offshore wind industry. *Renewable Energy*, *102*, 118–133. https://doi.org/10.1016/j.renene.2016.10.035

Ali, S., Stewart, R. A., Sahin, O., & Vieira, A. S. (2023). Integrated GIS-AHP-based approach for off-river pumped hydro energy storage site selection. *Applied Energy*, *337*, 120914. https://doi.org/10.1016/j.apenergy.2023.120914

Amin, C., Mulyati, H., Anggraini, E., & Kusumastanto, T. (2021). Impact of maritime logistics on archipelagic economic development in eastern Indonesia. *The Asian Journal of Shipping and Logistics*, *37*(2), 157–164. https://doi.org/10.1016/j.ajsl.2021.01.004

Ansofino, Z., & Zusmelia, Z. (2017). Towards economic linkages and market integration in facing ASEAN economic community: Case study West Sumatra economy. In *Int J Econ Res*.

Basia, L., Suripto, S., & Wiliyanto, E. (2025). Analisis faktor-faktor yang mempengaruhi impor beras di Indonesia. *Socius: Jurnal Penelitian Ilmu-Ilmu Sosial*. https://ojs.daarulhuda.or.id/index.php/Socius/article/view/1182

Benítez, J., Delgado-Galván, X., Gutiérrez, J. A., & Izquierdo, J. (2011). Balancing consistency and expert judgment in AHP. *Mathematical and Computer Modelling*, *54*(7–8), 1785–1790. https://doi.org/10.1016/j.mcm.2010.12.023

Berawi, M. A., Susantono, B., Miraj, P., Sari, M., Saroji, G., Berawi, A. R. B., & Sidqi, H. (2020). *Accelerating Nation Competitiveness Through Economic Corridor Development: Indonesia Masterplan Revisited* (pp. 77–100). https://doi.org/10.1007/978-3-030-60080-8_5

Bocarejo S., J. P., & Oviedo H., D. R. (2012). Transport accessibility and social inequities: a tool for identification of mobility needs and evaluation of transport investments. *Journal of Transport Geography*, *24*, 142–154. https://doi.org/10.1016/j.jtrangeo.2011.12.004

Burinskiene, A. (2022). Interconnection of freight delivery transport service networks. *2022 IEEE 28th International Conference on Engineering, Technology and Innovation (ICE/ITMC) & 31st International Association For Management of Technology (IAMOT) Joint Conference*, 1–9. https://doi.org/10.1109/ICE/ITMC-IAMOT55089.2022.10033135

Chou, C.-C. (2010). Ahp Model for The Container Port Choice in The Multiple-Ports Region. *Journal of Marine Science and Technology*, *18*(2). https://doi.org/10.51400/2709-6998.2321

Cullinane, K., & Wang, Y. (2009). A capacity-based measure of container port accessibility. *International Journal of Logistics Research and Applications*, *12*(2), 103–117. https://doi.org/10.1080/13675560902749340

Das, R. (2012). The Industrial Cluster Concept in Regional Economic Development Prospective: A Literature Review. *SEDME (Small Enterprises Development, Management & Extension Journal): A Worldwide Window on MSME Studies*, *39*(2), 65–76. https://doi.org/10.1177/0970846420120205

Delgado, M., Porter, M. E., & Stern, S. (2014). Clusters, convergence, and economic performance. *Research Policy*, *43*(10), 1785–1799. https://doi.org/10.1016/j.respol.2014.05.007

Donnadieu, F., Jessop, D., Bani, P., & Moune, S. (2022). Volcano Remote Sensing with Ground-Based Techniques. *Hazards and Monitoring of Volcanic Activity 2: Seismology, Deformation and Remote Sensing*. https://onlinelibrary.wiley.com/doi/10.1002/9781394169610.ch4

Dwitasari, R., Andriani, I., Herwening, M., Susanti, S., & Kuswati, A. S. (2021). Container Ports' Performance and Logistics Costs: A Case Study in Indonesia. In *International Conference on industrial Engineering and Operations Management*. https://ieomsociety.org/proceedings/2021indonesia/42.pdf

Gani, A. (2017). The Logistics Performance Effect in International Trade. *The Asian Journal of Shipping and Logistics*, *33*(4), 279–288. https://doi.org/10.1016/j.ajsl.2017.12.012

Guo, J., Wang, Z., & Yu, X. (2022). Accessibility measurement of China's coastal ports from a land-sea coordination perspective - An empirical study. *Journal of Transport Geography*, *105*, 103479. https://doi.org/10.1016/j.jtrangeo.2022.103479

Guo, T., Liu, P., Wang, C., Xie, J., Du, J., & Lim, M. K. (2023). Toward sustainable port-hinterland transportation: A holistic approach to design modal shift policy mixes. *Transportation Research Part A: Policy and Practice*, *174*, 103746. https://doi.org/10.1016/j.tra.2023.103746

Herdian, T., Simatupang, T. M., Basri, M. H., & Purqon, A. (2025). Legislation review in reconstructing Indonesia's hub ports policy. *Case Studies on Transport Policy*, *21*, 101528. https://doi.org/10.1016/j.cstp.2025.101528

Hu, Q., Wiegmans, B., Corman, F., & Lodewijks, G. (2019). Integration of inter-terminal transport and hinterland rail transport. *Flexible Services and Manufacturing Journal*, *31*(3), 807–831. https://doi.org/10.1007/s10696-019-09345-8

Indrawati, S. M., Satriawan, E., & Abdurohman. (2024). Indonesia's Fiscal Policy in the Aftermath of the Pandemic. *Bulletin of Indonesian Economic Studies*. https://doi.org/10.1080/00074918.2024.2335967

Isbaex, C., Costa, F. dos R. F., & Batista, T. (2025). Application of GIS in the Maritime-Port Sector: A Systematic Review. *Sustainability*, *17*(8), 3386. https://doi.org/10.3390/su17083386

Jarumaneeroj, P., Ramudhin, A., & Barnett Lawton, J. (2023). A connectivity-based approach to evaluating port importance in the global container shipping network. *Maritime Economics & Logistics*, *25*(3), 602–622. https://doi.org/10.1057/s41278-022-00243-9

Ji, X., Dong, F., Zheng, C., & Bu, N. (2022). The Influences of International Trade on Sustainable Economic Growth: An Economic Policy Perspective. *Sustainability*, *14*(5), 2781. https://doi.org/10.3390/su14052781

Juangsa, F. B., & Ahmad, A. H. (2025). Cofiring Technology Concept. *Decarbonizing Power Generation Sectors Using Biomass and Hydrogen-Based Fuels*. https://doi.org/10.1007/978-981-97-9360-0_3

Kotikov, J. (2017). GIS-Modeling of Multimodal Complex Road Network and Its Traffic Organization. *Transportation Research Procedia*, *20*, 340–346. https://doi.org/10.1016/j.trpro.2017.01.043

Kusumawardani, R., & Widyatmoko, A. A. (2024). Enhancing Pharma Manufacturing Efficiency: Integrating Lean Six Sigma and Fuzzy FMEA for Waste Reduction. *Spektrum Industri*. https://journal3.uad.ac.id/index.php/spektrum/article/view/199

Laksmana, T. (2020). *Investigating the Role of Government Support in the Resource-Process-Performance Relationship in Indonesian Container Terminal Operations: An Empirical Study*. vuir.vu.edu.au. https://vuir.vu.edu.au/41291/

Lee, S., Song, J., Park, S., & Sohn, B. (2014). A Study on the Comparative Analysis of Port Competitiveness Using AHP. *KMI International Journal of Maritime Affairs and Fisheries*, *6*(1), 53–71. https://doi.org/10.54007/ijmaf.2014.6.1.53

Lestari, E. (2021). impact of the development of Makassar new port (MNP) in supporting sea tolls. *Linguistics and Culture Review*, *5*(S1), 1265–1275. https://doi.org/10.21744/lingcure.v5nS1.1603

Li, L., Zhang, Q., Zhang, T., Zou, Y., & Zhao, X. (2023). Optimum Route and Transport Mode Selection of Multimodal Transport with Time Window under Uncertain Conditions. *Mathematics*, *11*(14), 3244. https://doi.org/10.3390/math11143244

Mutia, R. T. N., Archellie, R. De, & Darmoujuwono, S. (2019). Indonesia's cultural resilience responses to China's Belt and Road Initiatives: KEK Sei Mangkei as a Case Study. *International Review of Humanities Studies*. https://scholar.ui.ac.id/en/publications/indonesias-cultural-resilience-responses-to-chinas-belt-and-road-

Nguyen, T.-M.-T., Nguyen, D.-T., Truong, M.-H., & Doan, N.-A. (2021). GIS-based simulation for deep-water port site selection using analytic hierarchy process: a case study from Southern East of Vietnam. *Applied Geomatics*, *13*(1), 107–118. https://doi.org/10.1007/s12518-020-00319-2

Notteboom, T. E., & Rodrigue, J.-P. (2005). Port regionalization: towards a new phase in port development. *Maritime Policy & Management*, *32*(3), 297–313. https://doi.org/10.1080/03088830500139885

Papaioannou, D., & Wagner, N. (2019). Benchmarking accessibility in cities: measuring the impact of proximity and transport performance. In *International Transport Forum, Paris*.

Prastyabudi, W. A., Faharga, R. A., & Chandra, H. (2024). Systematic Risk Analysis of Railway Component Quality: Integration of Failure Mode &Effect Analysis (FMEA) and Fault Tree Analysis (FTA). *Spektrum Industri*. https://journal3.uad.ac.id/index.php/spektrum/article/view/223

Putri, E. P., Parinov, I. A., & Wongloucha, C. (2024). Efficiency Evaluation in Indonesia's Quarrying Industry Using Variable Combinations DEA. *Spektrum Industri*. https://journal3.uad.ac.id/index.php/spektrum/article/view/227

Sénquiz-Díaz, C. (2021). The Effect of Transport and Logistics on Trade Facilitation and Trade: A PLS-SEM Approach. *ECONOMICS*, *9*(2), 11–24. https://doi.org/10.2478/eoik-2021-0021

Sinaga, R., Priatna Humang, W., & Kurniawan, A. (2018). Potential cargo demand of Kuala Tanjung Port as international hub port in Western Indonesia. *MATEC Web of Conferences*, *181*, 09001. https://doi.org/10.1051/matecconf/201818109001

Skender, H. P., Host, A., & Nuhanovic, M. (2016). The role of logistics service providers in international trade. *Business Logistics in Modern Management*. https://hrcak.srce.hr/ojs/index.php/plusm/article/view/4667

Smith, G., & Hensher, D. A. (2020). Towards a framework for Mobility-as-a-Service policies. *Transport Policy*, *89*, 54–65. https://doi.org/10.1016/j.tranpol.2020.02.004

Sopha, B. M., Asih, A. M. S., & Nursitasari, P. D. (2018). Location planning of urban distribution center under uncertainty: A case study of Yogyakarta Special Region Province, Indonesia. *Journal of Industrial Engineering and Management*, *11*(3), 542. https://doi.org/10.3926/jiem.2581

Statistik, B. P. (2025). Data ekspor impor nasional. In *Retrieved from Badan Pusat Statistik: https://www. bps.*

Suryana, H. (2020). Aksesibilitas Pelabuhan Kuala Tanjung dalam Mendukung Kelancaran Arus Barang di Kawasan Ekonomi Khusus (KEK) Sei Mangkei, Provinsi Sumatera Utara. *Jurnal Media Teknik Dan Sistem Industri*, *4*(2), 91. https://doi.org/10.35194/jmtsi.v4i2.1058

Tampubolon, J., & Nababan, T. S. (2018). International Trade and North-Sumatra's Local Economy. *JEJAK*, *11*(2), 323–337. https://doi.org/10.15294/jejak.v11i2.16055

Valjarevic, A., Radovanovic, D., Soskic, S., Bacevic, N., Milentijevic, N., Golijanin, J., & Ivanovic, M. (2021). GIS and geographical analysis of the main harbors in the world. *Open Geosciences*, *13*(1), 639–650. https://doi.org/10.1515/geo-2020-0223

Wan, M., Kuang, H., Yu, Y., & Zhang, R. (2022). Evaluation of the competitiveness of the container multimodal port hub. *Scientific Reports*, *12*(1), 19334. https://doi.org/10.1038/s41598-022-23845-y

Wisnicki, B., Dybkowska-Stefek, D., Relisko-Rybak, J., & Kolanda, L. (2021). Methodology for Determining the Location of River Ports on a Modernized Waterway Based on Non-Cost Criteria: A Case Study of the Odra River Waterway. *Sustainability*, *13*(6), 3571. https://doi.org/10.3390/su13063571

Wulandary, D. D., Rivai, A. K., & Rahmi, R. (2022). Investigating Customer Satisfaction of the Bakauheni-Palembang Toll Road. *Jambura Science of Management*. https://ejurnal.ung.ac.id/index.php/jsm/article/view/11445

Yudha, Y. D. P., & Anwar, M. Z. K. (2025). Dampak Ekspor dan Impor Terhadap Pertumbuhan Ekonomi di Indonesia. In *Jurnal Riset Manajemen Dan Ekonomi (JRIME)*.

Yudhistira, M. H., & Sofiyandi, Y. (2018). Seaport status, port access, and regional economic development in Indonesia. *Maritime Economics & Logistics*, *20*(4), 549–568. https://doi.org/10.1057/s41278-017-0089-1