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Unlocking the Potentials of Artificial Intelligence in Enhancing Port Efficiency for Selected Asian Ports

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ABSTRACT

This research focuses on unlocking the potentials of artificial intelligence in enhancing port efficiency for selected Asian Ports. The purpose of this research is to examine the role of artificial intelligence in enhancing port efficiency for selected Asian Ports such as Belawan; Tanjung Priok; Tanjung Perak; Balikpapan and Makassar. The application of artificial intelligence technology in Ports demarcates and distinguishes a traditional port from a smart port. Smart ports make use of Drones, the Internet of Things (IoT), Artificial Intelligence (AI), Big Data Analytics etc . These trend in 4IR and Port operation signifies a critical shift in port operations. The ultimate reason for adopting any of these technologies is to enhance port productivity. A non -parametric tool known as the Data Envelopment Analysis Malmquist Productivity Index is used to determine the drivers of port productivity.

1. Introduction.

The maritime sector is intricately woven and very complex. This is because the process of moving freight from origin to destination involves a myriad of documentation as well as stakeholders. The port, shipping company, freight forwarders, importers, exporters, and various government agencies are critical players in the maritime supply chain. Notteboom et al (2022) affirm that the seaport is the connection between land and maritime space, a critical node where ocean and inland transport systems engage, and it is a place of convergence for different transportation modes. Dinh et al (2024) posit that Maritime transport forms the backbone of global logistics because it requires the transfer of bulk, break-bulk, containers, oil and gas etc. Due to the different capacities of the modes of maritime and inland transportation, the port assumes the role of nodal points where cargo is stored, consolidated, or deconsolidated (Notteboom, et al, 2022) (Ferretti et al, 2025). Sunitiyoso (2022) confirms that Indonesia's inter-island movement of goods depends mainly on sea transportation because it can transport large volumes of goods at a reasonable cost. This is the basis for the port evaluation.

Maritime transport is global in nature and it requires sophisticated planning due to the inherent challenges such as unpredictable weather, diverse types of cargo kinds, and changes in port conditions, all of which can raise operational costs (Dinh et,al 2024).

The unpredictability of port operations requires precision that artificial intelligence (AI) algorithms can provide. Aylak (2022) defines artificial intelligence as a technology that allows computers to mimic human thinking abilities. Even more than that, AI has predictive abilities that enhance decision-making. Sophisticated AI systems and structures can now design autonomous ships, which can operate without human interaction, and they have the lowest error rate compared to human-operated ships (Aylak, 2022). AI has the capacity to enhance port efficiency and effectiveness. Ghazaleh (2023) states thatartificial intelligence (AI) is not only digitalizing transportation at sea, on land, and in the air, it also has the potential to reduce, prevent human error and make operations faster. AI is a crucial for improving port operations (Ghazaleh, 2023). Safuan and Syafira(2024) affirm that artificial intelligence (AI) can augment operational efficiency, boost ship traffic management, and

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Table 1: Application of AI in Ports.

Author and Year	AI Procedure	Application Area
Alpaotis and Ipiotis (2025)	Decarbonisation	Enabler of Nuclear-powered Maritime Ships
Digh et al (2024)	Port Management System	Precision in the forecasting the lengths of ship stays and delays.
Lee et al (2025)	Resilience-based AX strategy and implementation system	Enhances domestic container-terminal companies to proactively respond to the upcoming changes in the global supply chain,
Ferretti et al (2025)	Cyber Physical Systems	Emission reduction
Pohontu, and Ermolai, (2024)	Maritime Domain Awareness	Safety and Security
Jiang, et al. (2024)	Spatial pyramid pooling (SPP) Multi Scale Context feature	Precision of Ship Segmentation
Singh et al (2024)	Machine learning	To support clean energy solutions and build a sustainable energy environment
Chen et al, (2024)	Automatic Identification System (AIS) Vessel trajectory Trajectory compression	Automatic Identification System-Based Vessel Trajectory Compression
Sarantopoulos, (2024).	Decarbonizing the Shipping industry through Innovative Technologies, AI	Optimizing shipping routes, predictive maintenance, and energy management,
Pérez-Canosa, et al (2024).	Making use of AI tools and training neural networks	Mathematical models were developed,
Sotirov, et al (2024)	Predictive Analytics	Predicting and managing risks for coastal port developments
Son, Kim, Lee, & Cho, (2024).	Analysis of extraction method for maritime traffic intensity zone through occupancy rate of Automatic Identification System datas.	Maritime Spatial Planning
Lin, et al, (2024).	Big data-driven booking	real-time batching algorithm, data-driven batching and scheduling algorithms,
Zhang, et al, (2024,)	Efficient Resource Allocation for Offshore Intelligent Navigational Aids Using Deep Reinforcement Learning.	Smart navigational aids
Kovalishin, et al, (2023).	AI methods for smart grid energy management optimization for ports	Smart grid concept
Tsolakis et al, (2021).	AI driven environmental sustainability	Robotics and Automated Guided Vehicles
Durlik, et al (2024).	Machine Learning	Application of AI in fuel optimization, predictive maintenance, route planning, and smart energy management,
Lee, et al (2023);	Novel mathematical framework rooted in deep learning techniques.	Identifies parking spaces and lanes in seaport environments based on crane positions, utilizing live Closed-Circuit Television (CCTV) camera data for real-time monitoring and efficient parking space allocation.
Bahari, et al, (2023)	Machine Learning Deep Learning	Application and forecasting approaches for sea level rise.

Source: Authors.

automate container handling activities within Indonesian ports.

There is a new paradigm shift in the world of port and maritime transport, and artificial intelligence transformation is at the center of this shift (Lee et al, 2025).

Osundiran and Tshehla (2025) affirm that the beauty of AI lies in its potential and ability to improve port performance, which will benefit import and export-led businesses. UNCTAD (2025) reiterates that performance monitoring is pivotal to evaluating efficiency and effectiveness and essential to supporting informed decision making, and safeguarding long-term resilience and competitiveness. Boadu et al (2025) asserts that delays, bottlenecks that affect port productivity and efficiency can be conquered through the successful adoption and synchronization of port automation and digitalization. Boadu et al (2025) state that port digitalization promotes safe, quick, and more economical port operation.

The Indonesian government affirms the essentiality of maritime logistics and supply chain as a major determinant for national development by making provision for the development of ports. (Suniyotso et al, 2022). The essence of evaluating key ports in Indonesia is based on the need for continuous improvement. Furthermore, to ascertain the various applications of Artificial Intelligence that these selected ports are implementing. Therefore, this research focuses on assessing major ports in Indonesia, such as Belawan, Balikpapan, Tanjung Priok, Tanjung Perak, and Makassar. The drivers of port productivity for the selected ports are ascertained.

The following is the outline of the paper, Section1.1 outlines the problem statement, research objectives and questions; Section 2 focuses on the literature review; Section 3 examines the methodology and approach, and Section 4 focuses on the results. This paper concludes with Section 6.

1.1. Problem Statement and Research Objective.

According to Robbany et al. (2022), service delivery and performance are a major challenge for the Port Authority of Indonesia. Port evaluation is important for improvement. The onus lies on Port management to make pivotal and timely decisions. The main objective of this research is to evaluate port performance and to determine the drivers of productivity for the selected ports of Belawan, Tanjung Priok, Tanjung Perak, Balikpapan, and Makassar from 2006 to 2024.

2. Review of Literature.

According to Mazibuko et al. (2024), a container port's tenacity is a function of the productivity of its container terminal operations. Indonesia, an archipelago island country, is advancing through the complexities of the fourth Industrial Revolution by adopting the smart port concept to enhance performance and operational efficiency (International Trade Administration ITA, 2024). Key Indonesian ports such as Kuala Tanjung, Cikarang Dryport, Tanjung Priok, Semarang Container Terminal, and Teluk Lamong have initiated smart technology upgrades (ITA,2024).

2.1. The Selected Indonesian Port.

Danladi et al., (2024) opine that Container ports serves as lifeline for facilitating international trade and promoting economic development. This principle applies to the port of Belawan; Tanjung Priok; Tanjung Perak; Balikpapan and Makassar. The pivotal role of ports to the Indonesian economy requires periodic evaluation of port performance and productivity. Belawan is among the most important ports in Indonesia (Listiani and Rathi, 2020). The Port of Tanjung Perak is the default entry point to Surabaya which handles more than 40% of international goods trade(Siahaan, et al, 2024). However, long queues is a typical feature for the Tanjung Perak port of Surabaya due to capacity issues (Hidaya et al, 2022).

2.2. Application of 4IR in Maritime in the Selected Asian Ports.

This section examines the various applications of 4IR in the selected Ports. Table 2 shows the application of AI amongs the selected Indonesian selected ports. The combination of Genetic Algorithm (AG) and Fuzzy Logic is used to reduce waiting time for ship services in ports, specifically in Belawan Port, Indonesia (Tinambunan et al, 2024). The integration of artificial intelligence (AI) within Indonesian ports is growing but experiencing difficulties with physical limitations, human capital, and regulatory frameworks (Safuan, and Syafira, 2024). Fahmi et al (2024) conducted a study to investigate the effectiveness of hazardous (B3) and non-hazardous (Non-B3) waste management at Tanjung Priok Port through the implementation of Reception Facilities (RF) to support the Green Port initiative. The Indonesian Ports of Balikpapan and Belawan implement the marineM digital platform (Smartmaritime network, 2025). Marine Operating System (MOS) will optimise marine services for arriving and departing vessels, such as allocating tug pilot and service boats. The Ports of Balikpapan and Belawan uses the software to digitize the entire pilotage process, optimise vessel and berth allocation, assisted by the software's AI-powered algorithms (Smartmaritime network, 2025).

Table 2: Application of AI in Indonesian Selected Ports.

S/N	Ports	Artificial Intelligence procedure	Application Area
1	Port of Belawan	Genetic Algorithm (AG) and Fuzzy Logic	Ship service scheduling
2	Port of Tanjung Priok	Reception facilities	Waste management
3	Port of Tanjung Perak	Genetic Algorithm (GA).	Reducing waiting time
4	Port of Balikpapan	AIS (Automatic Identification System)	Digitalise pilotage process
5	Port of Makassa	AIS (Automatic Identification System)	Vehicle traffic system and safety

Source: Authors.

2.3. The Importance of Data Envelopment Analysis (DEA).

According to Krmac, & Kaleibar (2025) port operations present challenges and complexities that require optimal management and strategic planning. Port evaluation using DEA enables port authorities to make correct decisions. The DEA reveals port efficiency and drivers of port productivity (Krmac, & Kaleibar 2025).

3. Research Methods.

The study is inclined towards a quantitative research design that makes use of secondary data extracted from the Indonesian port websites. Kao (2023) states that efficiency is calculated as the ratio of output to input. For this study, inputs are the number of container berths, the number of tug boats, number of cranes, length of the quay, whilst the output is the container throughput. This research makes use of a mono method, a Quantitative Research Approach. For the purpose of calculating efficiency, the inputs and outputs parameters are required.

Table 3: Input and Output.

Variables	Description
Number of Container Terminals	Input
Number of Container Berths	Input
Number of Tugs	Input
Length of Quay	Input
Container Throughput	Output

Source: Osundiran, 2025.

The inputs are the number of container berths, the number of tug boats, number of cranes, length of the quay, whilst the output are container throughput. This secondary data for 2006-2024 is sourced from Badan Pusat Statistics BPS Indonesian Statistics. Atsunyo & Tetteh (2025) states that the Malmquist index (MI) is a tool that compares and evaluates the efficiency change over time. In the non-parametric framework, it is measured as the product of catch-up (or recovery) and frontier-shift (or innovation) terms, both coming from the DEA technologies. Table 3 captures the inputs and outputs used in the calculation of the MPI. The Pim-Dea V.3.0 software, developed by Emrouznejad and Thanassoulis (2011), calculates the efficiency change for the selected ports from 2006 to 2024. Equation 1 captures the MPI formula.

Equation (1): The Malmquist Productivity Index Formula.

$$M(Y_{t+1}, X_{t+1}, X_t) = \underbrace{\frac{D^t(Y_{t+1}, X_{t+1})}{D^t(Y_t, X_t)}}_{\text{Efficiency change}} \underbrace{\left[\frac{D^t(Y_{t+1}, X_{t+1})}{D^{t+1}(Y_{t+1}, X_{t+1})} \times \frac{D^t(Y_t, X_t)}{D^{t+1}(Y_t, X_t)} \right]}_{\text{Technology change}}$$

Where:

X_t and X_{t+1} are input vectors of dimension n at time t and $t+1$, respectively. Y_t and Y_{t+1} are the corresponding k-dimensional output vectors. D^t and D^{t+1} denote the input distance functions

$$D(x, y) = \max \left\{ \rho : \left(\frac{s}{\rho s} \right) \in L(y) \right\}.$$

Where $L(y)$ represents the set of all input vectors with which a given output vector y can be produced, i.e.,

$$L(y) = \{x : \ y \text{ can be produced with } x\}.$$

The factor ρ in Equation (2) can be interpreted as the reciprocal of the factor by which total inputs can be proportionally reduced while maintaining the same output level.

The Malmquist productivity index, M, measures the productivity change between periods t and $t + 1$. Productivity declines if $M < 1$, remains unchanged if $M = 1$, and improves if $M > 1$.

4. Results and Discussion.

The port productivity of the five Indonesian ports are analysed for the period of 2006 till 2024 using the Pim-DEA V3.0. Results of these analysis are categorized into efficiency change, and technology change. The product of the efficiency changes and technology makes up the Malmquist Productivity Index.

4.1. The Efficiency Change.

The DEA approach provides individual efficiency scores for each port. A score of 1 on the efficiency scale indicates that the port is operating at its optimal efficiency and successfully utilizing its resources to achieve desired outcomes (Atsunyo & Tetteh ,2025). Values less than one show inefficiency, suggesting room for improving resource utilization (Atsunyo & Tetteh 2025). Table 4, shows the efficiency change for the selected ports. The Port of Belawan had on average 1,20, while the port of Tanjung Piok had on average 1.10, the Port of Tanjung Perak had on average 1.08. The Port of Balikpapan and Makassar had efficiency change of 1.03 and 1.06. Even though all the ports had EC>1 which shows progress in efficiency, there is still need to maintain consistency and continuity.

Table 4: Efficiency Change for the selected Indonesian Ports.

Ports	Efficiency Change																	
	2005 to 2007	2007 to 2008	2008 to 2009	2009 to 2010	2010 to 2011	2011 to 2012	2012 to 2013	2013 to 2014	2014 to 2015	2015 to 2016	2016 to 2017	2017 to 2018	2018 to 2019	2019 to 2020	2020 to 2021	2021 to 2022	2022 to 2023	2023 to 2024
Port of Belawan	0,97	1,03	1	1	1	0,88	0,98	0,79	0,79	0,97	1,27	0,59	2,55	0,28	1,25	2,82	1	1
Port of Tanjung Priok	0,97	1,13	1,12	1,93	0,67	0,96	1,01	0,91	1,11	0,94	0,92	1,04	0,75	1,13	1,05	0,76	1,05	1,03
Port of Tanjung Perak	1	0,89	1,13	1	0,65	0,91	0,97	0,98	1,09	0,97	1,17	0,79	1,15	0,83	1,23	1,56	1	1
Port of Balikpapan	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0,18	1,05	1,29
Port of Makassar	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Source: Osundiran, 2025.

4.2. Technology Change.

Technology is a major driver for port productivity. Technological change measures how the production frontier shifts over time. As the frontier shifts upward, more outputs can be obtained from the same level of inputs. Table 5, shows the technology change for the selected ports. There were several fluctuations in the technology change especially during the Covid 19-era. The Port of Belawan on average at TC of 1.07, the Port of Tanjung Priok had TC of 1.12; the Port of Tanjung Perak had TC of 1.13 whilst Port of Balikpapan had TC of 1.09 and 1.03 respectively. It is interesting to note that from 2020 till 2024, the selected ports shows increase of more than 1 in technology change.

Table 5: The Technology Change for the selected Indonesian Ports.

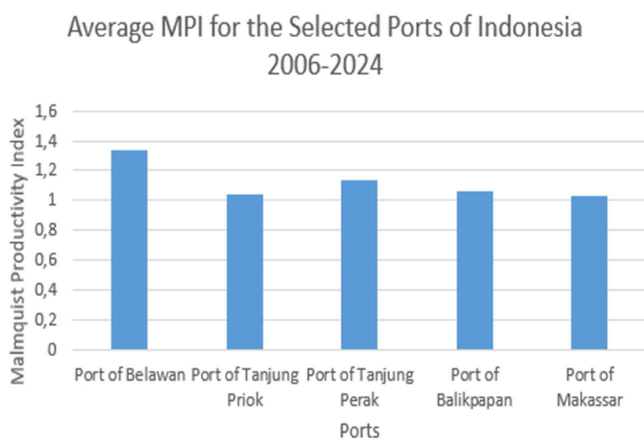
Ports	Efficiency Change																
	2006 to 2007	2007 to 2008	2008 to 2009	2009 to 2010	2010 to 2011	2011 to 2012	2012 to 2013	2013 to 2014	2014 to 2015	2015 to 2016	2016 to 2017	2017 to 2018	2018 to 2020	2019 to 2020	2021 to 2022	2022 to 2023	2023 to 2024
Port of Belawan	1,13	1,12	0,92	0,01	1,24	1,10	0,94	1,01	0,79	1,00	1,02	1,56	0,63	1,03	1,45	1,07	1,01
Port of Tanjung Priok	1,17	0,95	0,87	0	2,10	1,10	0,95	1,03	1,11	1,02	1,03	0,37	0,77	1,02	1,54	1,05	1
Port of Tanjung Perak	1,20	0,79	0,82	0	2,35	1,11	0,97	1,05	1,09	1,03	1,04	0,95	1,03	1,01	1,64	1,03	1
Port of Balikpapan	1,19	0,91	0,78	0	2,51	1,11	0,97	1,05	1,00	1,03	1,04	0,95	1,03	1,02	0,81	1,03	1
Port of Makassar	1,08	1,34	1,25	0,01	0,80	1,13	0,93	0,98	1,00	0,98	1,01	1,04	1,04	0,89	0,89	1,04	1,01

Source: Osundiran, 2025.

4.3. The Malmquist Productivity Index.

Atsunyo & Tetteh (2025), the Malmquist index summary underscores the importance of technological advancements and operational scalability in enhancing productivity. Figure 1 shows that the Port of Belawan ranks high with an average MPI of 1.33 whilst that of Tanjung Perak 1.13 while that of Makassar ranks 1.03. All the ports have productivity Index above 1. This is good as it indicates productivity level. Nevertheless, the ports must not rest on its oars. The Indonesian port management must continue to seek to improve port operations and service delivery.

Figure 1: Average MPI for the Selected Port of Indonesia 2006-2024.



Source: Osundiran, 2025.

5. Discussion.

This evaluation covers an 18 year period. The evaluation shows that technology is a major driver of productivity. Table 6, shows the various oscillations in the MPI. The MPI was affected by the pandemic as Ports like Belawan had MPI of 0.18 which is less than 1 between 2019 and 2020. The Port of Tanjung had MPI of 0.86. The Ports of Tanjung Perak, Balikpapan and Makassar had MPI of 0.84, 1.01 and 0.89 respectively during 2019 and 2020. Evidently the pandemic affected port productivity. Even though on the average the MPI is above 1 as indicated in Figure 1, this study suggests consistency, continuity and improvement.

Table 6: The Malmquist Productivity Index for the selected Indonesian Ports.

Ports	MPI																
	2006 to 2007	2007 to 2008	2008 to 2009	2009 to 2010	2010 to 2011	2011 to 2012	2012 to 2013	2013 to 2014	2014 to 2015	2015 to 2016	2016 to 2017	2017 to 2018	2018 to 2019	2019 to 2020	2021 to 2021	2022 to 2023	2023 to 2024
Port of Belawan	1,10	1,15	0,92	0,01	1,24	0,97	0,93	0,80	0,70	0,97	1,29	0,59	3,98	0,18	4,10	1,07	1,01
Port of Tanjung Priok	1,13	1,07	0,97	0,01	1,41	1,06	0,96	0,93	0,98	0,96	0,95	1,02	0,99	0,86	1,17	1,10	1,03
Port of Tanjung Perak	1,20	0,70	0,93	0	1,53	1,01	0,93	1,02	0,95	1,00	1,22	0,75	1,19	0,84	2,57	1,03	1,00
Port of Balikpapan	1,19	0,91	0,78	0	2,51	1,11	0,97	1,05	0,87	1,03	1,04	0,95	1,03	1,01	0,15	1,08	1,29
Port of Makassar	1,08	1,34	1,25	0,01	0,80	1,13	0,93	0,98	0,91	0,98	1,01	1,04	1,04	0,89	0,89	1,04	1,01

Source: Osundiran, 2025.

6. Conclusions.

Unlocking the potentials of artificial intelligence in enhancing port efficiency is paramount for the national growth and development. The essence of evaluating key ports in Indonesia is to provide the Indonesian Port Authority with valuable insight into port performance from 2006 to 2024. Thus research shows that technology has a critical role in port productivity. This research examined five Key Indonesian Ports, Port of Belawan, Port of Tanjung Priok, Port of Tanjung Perak,Port of Balikpapan, Port of Makassar, for the period of 2006 till 2024. The Malmquist Productivity Index was used to evaluate Port Productivity. All the Port on average had a slightly high MPI of greater than 1. This shows productivity. The research shows that technology is a major driver for port productivity.

Bokau et al, (2025) attest that port network makes up the interface between ships and land, which is particularly crucial in archipelagic nations of Indonesia. The correct, proper understanding of the effective utilisation of the opportunities afforded by artificial intelligence (AI), will position the Indonesian ports as front runners in the international maritime sector (Safuan, and Syafira, 2024). The efficient management of port services is essential for economic development as ports enable the import and export of goods, thereby contributing significantly to a country's gross domestic product (GDP) (Delfin-Ortega, 2025) . Enhancing the quality and speed of port services can lead to increased trade volumes, more robust economic growth, and improved connectivity in international markets.

Nevertheless, this research recommends continuous improvement, monitoring and evaluation as a basis for port growth and development for the Archipelago Island.

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