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Original Research Article

The Nexus Between Smart Port and Optimized Performance: A Study of the Lekki Deep Sea Port.

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ABSTRACT

This research investigated the nexus between the smart port and optimized performance at the LDSP. Members of the Nigeria Maritime Union of Workers and staff of the LDSP were the main respondents for the study. Multistage and random sampling techniques were employed in selecting the 125 respondents who participated in the study. The study had two objectives, the first, investigated the influence of Artificial Intelligence (AI) subsets of Machine Learning (ML) Robotics and Internet of Things (IoT) on the optimization of performance at the LDSP, an hypothesis was formulated and tested to achieve this objective, results from the Structural Equation Model (SEM) showed that the three subsets of AI significantly predicted optimized performance at the LDSP ML is significant at the 5% level (p=0.0). Robotics' is statistically significant at the 5% level (p=0.05), and 'Internet of Things' to 'LDSP Performance' is also significant at the 5% level (p=0.0). Result from the descriptive statistics indicated that AI tools (machine learning, robotics, and Internet of Things) positively impacted the performance of LDSP positively.It is suggested that investment in AI-driven new seaports should be prioritized as findings from this study have provided veritable insights into the benefits that accrued to the investors (in terms of profit), and sustainability ratings (in terms of environmental preservation).

Keywords: Artificial Intelligence, Smart Ports, Optimized Performance, Lekki Deep Seaport, Environmental Sustainability

1.0 INTRODUCTION

At the turn of the century, a pivotal paradigmatic shift occurred in the operational procedures across global ports (Zaman et al, 2017; Othman et al, 2022; Du, 2023; Ajayi, 2023; Xu et al, 2024). This revolution is driven by the inimitable roles of Artificial Intelligence (AI) in the analysis, integration, and operationalization of various activities in the maritime sector (Zaman et al, 2017; Othman et al, 2022; Du, 2023; Xu et al, 2024). Available evidence indicated that the utilization of AI in the shipping and logistics industry augments operational improvement in diverse strategic areas (Du, 2023; Xu et al, 2024). AI and its different subsets, like machine learning, deep learning, and big data analytics, has evolved into critical components of the maritime ecosystem to improve safety, efficiency, crew management, logistics optimization, fuel reduction, autonomous shipping, and sustainability (Hopf et al, 2023; Kolbjørnsrud,

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2024). These AI subsets are daily leveraged in the aforementioned important areas of the maritime sector and are seen by various stakeholders as the most significant repositioning impact on the sector thus far in the twenty-first century (Barbara et al, 2022; Li et al, 2023; Xu et al, 2024; Meranda et al, 2025).

The construction of AI infrastructures is woven by specialized chips and optimized algorithms that provide parallel processing, more precise calculations, and swifter memory access. The amalgam of the hardware and software allows AI to handle vast datasets, automate repetitive tasks, and process complex information at speeds and scales far beyond human capability (Hopf et al, 2023; Kolbjørnsrud, 2024). The conceptualization of AI in port management, create opportunity for the repetitive deployment of these specialized chips and optimized algorithms to engender safety, speed and sustainability while maintaining the precision required to prevent a systemic mishap that it effect can ripple across continental oceanic waterways (Barbara et al, 2022: Li et al, 2023: Xu et al, 2024: Meranda et al, 2025). Stakeholders in the maritime sector affirmed that AI has grown in relevance as the core infrastructure of global shipping, influencing decisions from berth allocation to emissions tracking (Hopf et al, 2023; Kolbjørnsrud, 2024; Meranda et al, 2025).

Shreds of evidence from different climes underscores the benefits that acquired to ports from investment in AI infrastructure, as the level of its adoption across strategic, tactical and operational functioning of ports are critical determinants of their competitiveness (Farzadmehr et al, 2023: Lawal-Fagbo et al, 2023; Li et al, 2023: Xu et al, 2024: Oni and Ajayi, 2025: Meranda et al, 2025). For example, the Port of Shanghai in China is considered one of the world's busiest container ports. In 2023 alone, it handled 47,303,000 Twenty-foot Equivalent Unit (TEUs), making it a crucial hub for international trade (Xi et al, 2024; Gocomet, 2025). Experts and stakeholders believed that the Port of Shanghai's recent success story cannot be detached from its robust digital architecture that allows cutting-edge machinery and equipment to handle huge ships and cargo efficiently, making it a leading port of destination globally (Gocomet, 2025). Similarly, the biggest seaport in Europe, the Port of Rotterdam is another prime example on how AI technology has been deployed to build intelligent systems to drive several AI-driven solutions, including a Vessel Traffic Management System (VTMS), and predictive maintenance operations for its infrastructure, automated container handling, and intelligent energy management systems to reduce environmental impact (Purani, 2025: Marc, 2025). These initiatives have tackled the incessant congestion, improved the level of safety, contributed to the sustainability ratings, and increased the competitiveness of the port, solidifying Rotterdam's position as a global maritime leader.

Also, the Port of Los Angeles, which incidentally is the busiest container port in the Western Hemisphere, has engaged AI in redesigning its cargo movement operations within its 135-acre fully automated TraPac terminal (Jacobs, 2025). The TraPac terminal is credited as the first port to deploy robotic shuttle carriers alongside driverless stacking cranes powered by electric, driverless shuttle carriers that operate an intelligent system propelled Global Positioning System, magnets, and lasers as it powering system. Experiential facts indicated that the holistic adoption of AI in the agglomeration of the processes has increased efficiency, reliability, and safety, and enhanced the sustainability ratings of the port (Jacobs, 2025; Zhong, 2025).

The conceptualization and construction of the LDSP is a response to nagging needs in the BE and international trade sectors of the country and the quest for Nigeria's ports to be securely positioned as the regional port-of-destination in the West/Central Africa region (Omoke et al, 2017; Ugboma & Oyesiku, 2020; Lawal-Fagbo et al, 2023; Ajayi, 2023; Meranda et al, 2025). Available statistics indicated that despite the preponderance of its trade volume when compared to other countries in the region, Nigeria's ports lagged behind neighboring ports in Ghana, Togo, and the Ivory Coast in terms of container traffic and overall cargo handling capacity in the pre-LDSP era (Larnyoh, 2020; Klein, 2023). The appalling state of Nigeria's maritime sector is such that the existing infrastructure, the operational framework, and the quality of the expertise available in the sector were incapable of driving the growth needed to position it as the regional shipping hub (Akinyemi, 2016; Lawal-Fagbo et al., 2023; Ajayi, 2023; Irinyemi, 2024).

One of the long-term plans is to onboard the LDSP and other deep seaports. The LDSP, built at USD 1.5 bn, is the country's first deepwater port, designed to take care of 1.2 million standard containers yearly; the LDSP was built to champion Nigeria's growing influence as a maritime transport hub in West Africa. The LDSP is equipped with 13 cranes for a capacity of 2.5 million twenty-foot equivalent units (TEUs) on a 1.2-km quay with a depth of 16 meters. It is built to process large cargo ships with a capability of up to 15,000 TEUs, previously diverted to other regional ports. The new facility is designed to help attract traffic destined for the region's landlocked countries, such as Niger, which has negotiated with the Nigerian Ports Authority (NPA) for the use of Lekki Port to transport goods to and from the country (Oxford Business Group, 2024). It is instructive that the new LDSP presently ranks third behind the Lome (Togo) and Tema (Ghana) seaports in terms of volumes in TUEs in the West Africa sub-region and is not presently listed among the top ten seaports in the African region (Africa News, 2024).

This research, therefore, filled a lacuna in available literature in the field by investigating the impact of AI on the characterization of the operations of the LDSP and the coastal environment where the LDSP is located. It is observed that the effective implementation of the Blue Economy (BE) agenda depends on the diffusion of digitalization in maritime transport operations and the growth of blue biotechnologies in the management of the marine environment and its biodiversity conservation (Pace et al., 2023; Gesami & Nunno, 2024; March et al., 2024). It has been discovered that an important pillar of BE is the irreplaceable role of robotics in the management of maritime business-related activities (Ajayi, 2023). Relatable experience has proven that the spread of AI-driven ports is one of the best contemporary practices for managing maritime hubs. Stakeholders in the sector posited that the deployment of AI in ports usually involves integrating interconnected sensors, data analytics, and intelligent systems to improve efficiency, security, and sustainability. (Gesami and Nunno, 2024; March et al., 2024; Xu et al., 2024).

2.0 Literature Review

Artificial Intelligence (AI) is globally acclaimed as a transformative technology in port development, enhancing operational efficiency, reducing costs, and improving safety. The application of AI in port operations revolves around the automation and optimization of various processes such as cargo handling, predictive maintenance, and logistics management, which are crucial to meeting the demands of global trade (Yang et al., 2021). Heilig et al. (2017) observed that AI-driven predictive analytics allow ports to anticipate and address maintenance needs proactively, reducing downtime and improving the reliability of port infrastructure. This scenario occurs more regularly in large ports, where even minor delays can result to loss of investment due to high cargo volumes and tight schedules.

The application of AI in ports management is also catalyzing the ability to streamline logistics processes by quickening decision-making and resource allocation functions. Advanced algorithms are deployed to analyze ship arrivals, departures, and cargo movement processes, enabling ports to optimize berthing schedules and reduce waiting times (Qi and Wu, 2020). AI-driven systems are also usually annexed to manage real-time data on port congestion, vessel traffic, and weather patterns, further enhancing the accuracy and efficiency of port operations. For instance, in their study on the impact of AI in smart ports, Lam et al. (2018) opined that the role of machine learning algorithms in resource planning has significantly improved the scheduling and allocation of port assets.

Furthermore, contemporary scholars affirmed that the introduction of AI in port security architecture has re-positioned the internal security outlay in most ports in recent years (Lam et al, 2018: Qi and Wu, 2022), as it is often deployed as scanners to unveil potential security breaches. Machine learning models are utilized in the identification of unusual patterns in cargo and personnel movements, strengthening the port's ability to prevent illegal activities (Liu & Fan, 2022). Conversely, AI contributes to a more secure and resilient supply chain by helping authorities preemptively identify risks.

However, holistic adoption and implementation of AI in ports is not without some challenges, particularly in aspects of data integration and cybersecurity (Carlan et al, 2019). Ports activties are data driven, such data-rich environments

usually create challenges of integrating diverse data sources across various systems, and this can be complex operations (Carlan et al., 2019). Additionally, and perhaps more worrisome is the cybersecurity concerns that arises as ports become increasingly digitalized, exposing critical infrastructure to potential cyber-attacks (Heilig et al., 2017; Lam et al., 2018).
Conversely, AI is an inimitable asset in port development, contributing to operational efficiency, safety, and cost-effectiveness. As ports continue to adopt AI, future research is essential to address the challenges of data management and cybersecurity to maximize AI's benefits in the maritime sector (Heilig et al., 2017; Lam et al., 2018; Liu & Fan, 2022).

This study analyzes the confluence between the optimization of AI as a tool for promoting port operations and the attainment sustainability goals, attention to such interrelationship is highly relevant in today's technologically driven world. Experiences from other clime has shown that AI can transform port management by enabling predictive maintenance, optimizing cargo handling, reducing downtime, and improving overall efficiency (Lam et al., 2018; Liu & Fan, 2022). As Nigerian ports repositioned themselves as regional maritime hubs, it is imperative that, they embrace advanced technologies, understanding how AI can enhance operations and contribute to sustainable practices becomes crucial. This research provides critical introspection into the practical applications of AI within port systems, promoting an understanding of how such technologies can be harnessed for economic and environmental gains. Additionally, the findings offers' a roadmap for other Nigerian seaports seeking to redesign and integrate innovative technologies, ultimately improving the nation's global maritime industry competitiveness.

Also, this study unraveled the function of AI and advanced technologies in ameliorating port operations and sustainability. By assessing how AI tools can optimize logistics, improve security, and monitor environmental parameters, the study offers insights into the potential of technological innovation to increase the efficiency of Nigeria's maritime sector. AI-driven solutions, such as predictive maintenance, automated cargo handling, and real-time environmental data monitoring, are considered within the context of their applicability and potential to shape sustainable port practices. The scope includes reviewing current technological advancements and the feasibility of implementing these solutions within the LDSP and similar infrastructural projects.

Literature research indicated that previous studies in this area have investigated the influence of AI transformation on the achievement of an increase in port performances as evidenced by a reduction in processing time for increasing cargo volumes, reduced operational costs, and the attainment of stringent environmental regulations in existing ports (Xu et al, 2024). However, a gap exists in how the workforce of a newly constructed smart port has been able to effectively utilize AI subsets of Machine Learning (ML), robotics, Non-Intrusive Inspection Systems (NIS), and Internet of Things (IoT) for monitoring and optimizing port operations (Al Rousam, 2024; Xu et al., 2024).

There is also a dearth of studies that focuses on the utilization of AI as a monitoring and management tool for oceanic resources in a smart or AI-driven port using the perceptions of employees within the port to ascertain this. The practical implications of this research are significant, as experiential knowledge showed that perception studies offer numerous benefits, including improving strategic decisions by providing data-driven insights into respondents' views on topical issues (Ajayi, 2010; Lagerkvist et al, 2021; Ajayi, 2023). Some earlier studies on the discourse affirmed the importance of deploying AI for detecting and identifying marine environmental pollution due to port activities (Zare et al, 2025).

Similarly, Ioras and Bandara (2025) investigated how AI was used to aid environmental decision-making by helping to process complex data, anticipate outcomes, and fine-tune day-to-day operations in busy coastal zones that house touristic facilities. This research provides exploratory insights into the utilization of AI in optimizing vessel routes and port traffic flow to reduce fuel consumption and predictive maintenance to ensure efficient asset use and waste reduction.

Occasioned by its burgeoning population growth and the attendant opportunities of having one of the biggest economies in the African region, salient questions were being asked on the competitiveness of the Nigeria's ports and its supply chain agility (measured by the data on vessel traffic, cargo throughput, and container traffic) when compared to ports that catered for similar population size (Table 1), that are designed for similar regional responsibilities in other parts of the world (Akinyemi, 2016: Omoke et al, 2017). The short-term response to the identified problems was the reforms of the ownership structures of the Lagos seaports by inviting private sector investment and improving the intermodal capacity of the ports (Akinyemi, 2016; Omoke et al., 2017). Findings indicated that there was an immediate impact or improvement in the operational efficiency of the ports post-concessionaire era; available statistics estimated that the port concession program had saved the country a total of $1.6bn, roughly $100m annually between 2006 and 2022 (Oxford Business Group, 2024).

2.1 Theoretical Underpinnings

This section is dedicated to the exposition of the theoretical framework for the study. This study derives a framework by combining two theories, namely: (1) Port Regionalization Theory, (2) The Digital Innovation Theory (DIT).

2.1.1 Port Regionalization Theory

The Port Regionalization Theory, as advanced from the seminal works of Notteboom and Rodrigue (2005), provides a pivotal framework for a comprehensive study of the interaction between port development and the development of the blue economy at the national, regional and the global levels. The construct of the theory indicates that modern ports, like the LDSP in Nigeria, are increasingly becoming integrated into broader regional and global logistics networks and are playing multidimensional integrative roles in the global supply chain architecture (Pace et al, 2023; Ajayi, 2023[2]). The theory affirms that ports are not just isolated transit points; they are key components of an international network, playing an essential role in facilitating economic activities and connecting regions to international markets.

Proponents of the Port Regionalization Theory argue that port infrastructural development goes beyond merely expanding physical facilities; it encompasses strengthening the port's position within a regional economic system. This transformation is significant in deep-sea ports, where the operational goal is toward the enhancement of ports' operational capacity to accommodate larger vessels and handle greater cargo volumes (Notteboom & Rodrigue, 2005). The conceptualization of the LDSP, as a smart port with AI-powered modern infrastructure and deepened water draught, fit this bill. By designating it as a smart port with a regional market, the Lekki Seaport is designed to attract larger vessels and facilitate the movement of more significant cargo, thereby enhancing the port's role in global and regional trade networks.

Scholars generally posited that the onboarding of ports like LDSP contributes directly to the growth of the blue economy, which involves salient economic functionalities that rely on marine resources and contribute to sustainable development (Lawal-Fagbo et al, 2023; Meranda et al, 2025). As critiqued by Notteboom and Rodrigue (2005), efficient and modern ports catalyze reduction in shipping costs, enhances trade facilitation, and improves connectivity among trade partners within regional and global markets. The expected increment in trade facilitation from the onboarding of the LDSP is pivotal for Nigeria's unlocking new opportunities within the blue economy. Indubitably, when fully operational the LDSP is expected to reduce the country's reliance on neighboring ports, such as the Port of Lomé in Togo and the Port of Cotonou in Benin, which currently handle significant volumes of Nigerian trade (Ajayi, 2023; Lawal-Fagbo et al, 2023; Meranda et al, 2025). By becoming the country's flagship smart port, the Lekki Seaport is expected to promote trade growth between Nigeria and her various trade partners and support the development of maritime-related sectors like logistics, manufacturing, and offshore energy production.

Furthermore, it has been discovered that smart ports like LDSP are harbingers of regional economic growth by triggering the development of surrounding industries and services (Oni & Ajayi, 2025; Meranda et al, 2025). In the comparatively short period after the launching of LDSP, a ripple effect of its impact is already noticeable in allied sectors such as transportation, logistics, and construction, generating direct and indirect employment opportunities (Oni & Ajayi, 2025). Expectation is rife that as the port attracts more trade and investment, it will ultimately stimulate industrialization and create new markets for goods and services, which, in turn, engender development of different sectors of the economy. As revealed by the analysis in Table 1, the advent of the LDSP has positively increased the performance of the maritime sector in Nigeria, when compared to competing ports in the West African sub-region. It has been established that growth in the different sectors creates an interdependence of the national economy essential for the successful implementation of the blue economy, which depends on a holistic approach to economic development that includes the sustainable management of marine and coastal resources (Pace et al., 2023).

Conversely, the LDSP development aligns with Nigeria's broader strategy to position itself as a key player in the Gulf of Guinea's maritime sector, the Gulf can be described a large inlet of the Atlantic Ocean off the western coast of Africa, it extends from Cape Lopez in Gabon in central Africa to Cape Palmas in Liberia in west Africa. It is an emerging region of global economic importance popular for its rich biodiversity, substantial offshore oil and gas deposits, and important shipping routes. As a regional logistics hub, the Lekki Seaport is expected to enhance Nigeria's competitiveness in the Gulf of Guinea, helping to attract investments and strengthen the country's maritime infrastructure (United Nations Conference on Trade and Development, 2018).

2.1.2. The Diffusion of Innovation Theory and its Applicability in Maritime Research

The Diffusion of Innovations Theory is a hypothetical construct that outlines the roles of novel technological advancement in the spread of development throughout societies and cultures, from introduction to widespread adoption. The DIT diffusion provides a theoretical lens on how and why new ideas and practices are adopted in different industries or societies and the critical determinants of the speed of the adoption of these new ideas over time (Rogers, 1962; Sonis, 2009; Brooks et al., 2016; Accario & Sys, 2020; Halton, 2023).

The DIT has been applied severally in the fields of business management, marketing, public health, educational management, and maritime research (Rogers, 1962; Sonis, 2009: Accario and Sys, 2020: Halton, 2023) DIT possesses some inherent characteristics; these are known as the five-step process that an individual or organization goes through when adopting a new idea or product. These stages are innovators, early adopters, early majority, late majority, and laggard. This theory explains how an idea or object is spread and adopted by many individuals, be it in an organizational or societal context (Sonis, 2009; Halton, 2023). The utilization of DIT in the present study hinged on the inevitability of adopting AI in managing the new LDSP and the appraisal of its successes and challenges. At the same time, findings from different studies in the maritime research domain suggest that numerous innovations have been adopted to automate a wide range of

Table 1: Analysis of the Operations of Container Handling Capacity (Twenty-foot Equivalent Units) Among Leading Ports in West and Central Africa

S/n	Name of Port	Country	Volume of Containers (TEUs) Handled 2022	Volume of Containers (TEUs) Handled 2023	Volume of Containers (TEUs) Handled 2024
1	Lome	Togo	1,982,879	1,907,439	2,000,001
2	Lagos	Nigeria	1,137,000	1,591,194	1,744,972
3	Tema	Ghana	1,200,405	-	1,701,246
4	Abidjan	Cote d' ivorie	840,926	1,238,195	1,650,010
5	Dakar	Senegal	738,029	800,068	887,289
6	Lekki	Nigeria	-	54,289	287,000

Source: Authors' Analysis, 2025

administrative and technical processes and building databases and networks to provide better services.

There is a gap to be filled in the appraisal of the applicability of AI in the management of the LDSP. The application of DIT in this research presents an opportunity to examine the essential characteristics of the studied population and place them in one of the five adopter categories to determine the most effective way to appeal to that specific population segment. Moreover, the utilization of DIT, as done in the study, provides an objective assessment of the pattern and speed at which new ideas, practices, or products introduced by the infusion of AI into the port activities spread through the studied population.

The extensive review of the literature and theoretical constructions as done in the study guided the overarching goal of this research, which is to evaluate the impact of the AI subsets of Machine Learning, Robotics, and Internet of Things on the achievement of optimized performance at the LDSP in its quest as a Smart Port. The study also investigated how AI has helped achieve the port's environmental management. To achieve the first objective, a hypothesis is derived that succinctly captures the objective:

H1: AI subsets of Machine Learning (ML), Robotics, and Internet of Things (IoT) have significantly influenced the achievement of optimized performance in LDSP as a Smart Port.

The second objective of this study, which examined the impact of AI on the attainment of environmental sustainability of the port, was achieved through a descriptive statistical tool.

3.0 Materials and Methods

This study employed a quantitative technique. Ethical considerations for the research were obtained from the ethical committee of Redeemer's University, Ede. Each respondent was duly informed of his/her ethical rights before being sampled. The staff of the LDSP, as represented by the members of the Maritime Union of Workers of Nigeria (MUWN), represented the primary respondents for this study. These respondents are critical components of the study's quest to objectively analyze the roles of AI and port operations in attaining BE growth in LDSP in Nigeria. They are also the most appropriate sources of information for achieving the study's objective, as they possess both the experiential and experimental knowledge of AI adoption at the LDSP. A pre-field exercise was undertaken to get a working knowledge of the terrain of the study area and to unravel the best technique to apply for sampling the respondents. As a derivative of the pre-field exercise, the multistage sampling is deemed the most appropriate to select the participants for the study.

The workforce of the LDSP is organized under the umbrella body of workers in the facility. The Maritime Union of Workers of Nigeria (MUWN) is this body; four affiliates of NMUW are represented at the LDSP, as shown in Table 2. The Dockworkers, Seamen, Shipping/Clearing Agents, and the Nigerian Port Authority (NPA) staff are affiliates. Records obtained from the MUWN secretariat indicated that two thousand four hundred and ninety-eight (2489) union-registered members are working at the LDSP. This figure represents the sample population of the workforce at the study site.

Ten percent of the workforce (253) was selected at the first stage as the population for the study. This aligns with the established norm in the available literature on determining sample size when applying a multistage sampling technique and using secondary data (Ajayi, 2020; Sathyanarayana et al., 2024). This is the first stage of the multistage sampling technique; in the second stage, an attempt was made to randomly sample every even-numbered member available in the list of the MUWN (from the 253 selected at the first stage). Eventually, 125 members of the MUWN were the respondents who participated in the study (Table 2).

Table 2. Breakdown of the Members of Maritime Union of Workers of Nigeria (MUWN) that Represent the Workforce at the LDSP and their Sample Size

S/N	Section	Number of Staff in the Unit	Ten Percent of the Staff	Sample Size
1	Dockworkers	1524	153	77
2	Seamen Unit	504	51	26
3	Shipping/Clearing Agents	218	22	11
4	Nigeria Port Authority (NPA) Administration Staff	50	05	03
5	NPA Information and Communication Technology/Pilotage Staff	78	08	04
6	NPA Logistics Staff	72	08	04
7	NPA Warehouse and Inventory Staff	52	06	03
	Total	2498	253	128

Source: Authors' Fieldwork, 2025.

The sampling took place over 3 months, and the members of each of the seven units of NMUW were sampled through their association registers. One hundred thirty-eight respondents were sampled (ten questionnaires were added to account for poorly completed or lost ones). One hundred twenty-five copies of the questionnaire, representing nearly 91% of the distributed research instrument, were retrieved. The questionnaires contained pre-tested items that measured the study objective. The surveys for the passengers were comprised of five sections, and it was organized thus: i) socio-economic demographics of respondents, ii) perceptions of respondents on whether the application of Artificial Intelligence subsets of Machine Learning, Robotics, and Internet of Things has improved efficiency of operations at the LDSP. iii) respondents belief if the benefits that are gotten from the investment in AI tools for operations at the LDSP are more than the costs of their acquisition iv) Respondents' perceptions on the availability of periodic on capacity building seminars organized by the management of the LDSP for staff and its influence as a bridge to the ICT skill deficiency gaps (v) The assessment of ICT and AI at the LDSP on the reduction of the risk of environmental mismanagement at the LDSP. The study site was visited for a period of one month.

4.0 Results

This section is dedicated to the results obtained through the research instrument utilized in the research.

4.1 Demographic Analysis

The demographic results (Table 3) of the respondents show an even spread across the age brackets from 21-30 years (22.4%), 31- 40 years (24.8%), and 41- 50 years (20%). A cumulative percentage of 67.2% suggests that most are young adults and belong to the active working-class age group. Further results indicate that a significant majority of the respondents are married (60%), providing a clear social context for our research. Additionally, most have at least a first degree (cumulative-68.8%).

Table 3 – Demographic Distribution

Demography	Classifications	Frequency	Percent
Age	21-30yrs	28	22.4
	31-40yrs	31	24.8
	41-50yrs	25	20
	51-60yrs	19	15.2
	61-65yrs	22	17.6
Marital Status	Single	26	20.8
	Married	75	60
	Separated	5	4
	Divorced	9	7.2
	Widowed	10	8
Position	Inter/Fresh Recruit	25	20
	Line Manager	34	27.2
	Admin Manager	33	26.4
	Senior Manager	26	20.8
	Executive Manager	5	4
	Others	2	1.6
Education	Primary School Cert.	9	7.2

	SSCE	5	4
	ND/NCE	23	18.4
	BSc/BA/HND	60	48
	PGD/MBA/MSc/MA	26	20.8
	Others	2	1.6
Years of Experience	1-5yrs	22	17.6
	6-10yrs	32	25.6
	11-15yrs	16	12.8
	16-20yrs	31	24.8
	21yrs and above	24	19.2
Job Function	Stevedore	29	23.2
	Dockworker	42	33.6
	Shipping Officer	21	16.8
	Pilotage Officer	17	13.6
	Others	16	12.8
ICT Savviness	Exceptional	24	19.2
	High	17	13.6
	Medium	70	56
	Low	14	11.2
Valid	Total N	125	100

Source: SPSS Outputs (2025)

Results from Table 3 show that the respondents are evenly spread across the various job positions in the organization, allowing for a balanced opinion on the study's objectives. The number of years on the job also indicates that the majority are well-experienced with more than 10years (cumulative-56.8%). The distribution of the job responsibilities reveals that most are dockworkers (33.6%) and are closely followed by Stevedore professionals (23.2%). Furthermore, the respondents' response to their ICT competence suggests that almost all the respondents have at least a medium savviness (cumulative 88.8%), which justifies their employability since the LDSP is an AI-driven port, indicating their suitability as respondents on the subject matter.

4.2 Descriptive Analysis of Study Objectives

This section provides the descriptive analysis, which involves [explanation of descriptive analysis], done to realize the study’s objectives.

A binary scale (Yes -1, No -1) was used to capture responses to the underlisted question items, in order to specify the relationship between Artificial Intelligence (AI) and LDSP performance. The descriptive statistics of these responses are presented in Table 4.

Table 4 – Analysis of Descriptive Statistics

Items	N	Yes	No	Mean	Std. Deviation
Do you agree that the application of Artificial Intelligence subsets of Machine Learning, Robotics and Internet of Things has improved efficiency of operations at the LDSP?	125	73 (58.4)	52 (41.6%)	0.58	0.495
Do you believe that the benefits that are gotten from the investment in AI tools for operations at the LDSP are more than the costs of their acquisition?	125	67 (53.6%)	58 (46.4%)	0.54	0.501
Are there periodic training or capacity building seminars organized by the management of the LDSP for staff to bridge the ICT skill deficiency gaps?	125	58 (46.4%)	67 (53.6%)	0.46	0.501
The use of AI at the LDSP has greatly reduced the risk of environmental mismanagement at the LDSP?	125	78 (62.4%)	47 (37.6%)	0.62	0.486
Has the utilization of AI helped in reduction of emission, in the optimization of vessel routes and port traffic flow, and predictive maintenance to ensure efficient asset use and waste management at the LDSP?	125	80 (64%)	45 (36%)	0.64	0.483

Source: Authors' analysis (2025)

The result from Table 4 reveals the respondents' affirmation that AI tools (machine learning, robotics, and the Internet of Things) have improved operational efficiency at the LDSP (58.4%). The mean score of 0.58, with a standard deviation of 0.495, also suggests that this position holds firmly among the sampled workers in LDSP.

Similarly, there is a general belief that the benefits derived from investing in AI tools for operations far outweigh the cost of acquisition (53.6%). The mean score (0.54) and standard deviation (0.50) support this assertion. Furthermore, most respondents (53.6%) think there are no periodic training/capacity building seminars to bridge the ICT skills deficiency. This consensus is corroborated by the mean response (0.46) and standard deviation (0.50). Lastly, most of the respondents have observed using ICT and AI to significantly reduce the risk of environmental mismanagement at LDSP (62.4%). A mean score (0.62) closes to 1 and a low standard deviation implies this is a general belief. This result depicts one of the study's objectives: to investigate the nexus between the utilization of AI and the reduction of environmental mismanagement at the LDSP.

The summary of the descriptive statistics suggests that while AI tools (machine learning, robotics, and Internet of Things) have been perceived to impact the performance of LDSP positively, the organization's management can do better in ICT skill development for its staff.

4.3 Model Specification for the Derived Hypothesis

A Structural Equation Model (SEM) was used to specify the relationship among the variables in objective two. The intention was to transform the indicators of the various constructs in the research questionnaire into latent variables to explore their relationship. The SEM framework is presented below:

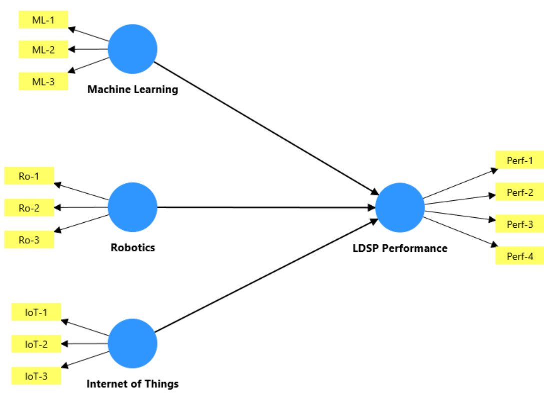

Figure 1: SEM framework
Source: Smart PLS-4 (2025)

The measurement equations for each of the constructions are:

Machine Learning (ML) = $f_{i1}ML_i + e_{i1}$………………….. (1)
Robotics (Ro) = $f_{i2}Ro_i + e_{i2}$………………….. (2)
Internet of Things (IoT)= $f_{i3}IoT_i + e_{i3}$……………….... (3)
LDSP Performance (Perf)= $f_{i4}Perf_i + e_{i4}$…………………. (4)

Where, f_{i1}, f_{i2}, f_{i3} and f_{i4} are the factor loadings for the question items. ML_i, Ro_i, IoT_i and $Perf_i$ are the items in the questionnaire.

4.4 Estimation Techniques for the SEM

The Partial Least Squares Structural Equation Model (PLS-SEM) technique was adopted and used in inferential analysis. The standardized factor loading, Cronbach alpha statistics, composite reliability and the average variance extracted were used for the model assessment, while the Fornel-Larcker and the Heterotrait-Monotrait (HTMT) criteria were used to test the discriminant validity. The Smart-pls 4 software aided the computations.

4.5 Assessment of the Structural Model

Table 5 shows the result of the assessment of the structural model. The factor loading requirement is a minimum acceptable value of 0.6, and only question items that meet this condition are retained for the path analysis. The retained indicators are listed in Table 1 and are considered fit to measure their respective constructions. Furthermore, the Cronbach alpha statistics show that two constructions have values below the minimum acceptable threshold of 0.6. However, the composite reliability statistics further reveal that the variables have no reliability problem, since the values are above the 0.6 benchmark. Thus, establishing that the items are all reliable in jointly measuring their individual constructs.

The Average Variance Extracted (AVE) was computed to determine the convergent validity and ensure that the measurement items of the constructs are related. The minimum acceptable requirement is 0.5, and the results in Table 1 imply that the construction variables have an AVE above this threshold.

Table 5 – Model Assessment Parameters

Construct	Indicators	Loadings	Cronbach's Alpha	Composite Reliability	Average Variance Extracted (AVE)
Machine Learning (ML)	ML-1	0.847	0.697	0.832	0.624
	ML-2	0.769			
	ML-3	0.75			
Robotics (Ro)	Ro-2	0.702	0.454	0.778	0.640
	Ro-3	0.887			
Internet of Things (IoT)	IoT-1	0.838	0.483	0.794	0.658
	IoT-2	0.784			
LDSP Performance (Perf)	Perf-2	0.878	0.678	0.861	0.756
	Perf-3	0.861			

Source: Smart-PLS-4 (2025)

4.6 Discriminant Validity

The Fornell-Larcker and Heterotrait-Monotrait (HTMT) criteria were used to ascertain the construct variables' discriminant validity; the results are presented in Tables 6 and 7.

The Fornell-Larcker criterion requires that the square root of the AVEs (bolded values) be greater than the inter-construct correlations (unbolded values). The results in Table 6 show that this condition is satisfied. Similarly, none of the HTMT ratios in Table 7 exceed the maximum threshold of 0.9, which also ascertains that there is no problem of discriminant validity among the construct variables.

Table 6 – Fornell-Larcker Results

	Internet of Things	LDSP Performance	Machine Learning	Robotics
Internet of Things	0.811			
LDSP Performance	0.541	0.870		
Machine Learning	0.459	0.584	0.7900	
Robotics	0.139	0.369	0.269	0.8000

Source: Smart PLS-4 (2025)

Table 7 – Heterotrait-Monotrait (HTMT)

	Internet of Things	LDSP Performance	Machine Learning	Robotics
Internet of Things				
LDSP Performance	0.842			
Machine Learning	0.788	0.847		
Robotics	0.363	0.642	0.532	

Source: Smart PLS-4 (2025)

4.7 Model Fit

Table 8 shows the result of the goodness-of-fit criteria for the structural model. The model's Standardized Root Mean Squared Error (SRMR) is 0.113, above the maximum acceptable benchmark of 0.08. Furthermore, the model fit indices (dULS=0.572 & dG=0.238) are below the acceptable benchmarks (HI95. =1.74 & 1.27 respectively). In addition, the R-squared value of 0.468 implies that the explanatory variables jointly explain 46.8percent of the total variation in the exploratory variable. The summary of the structural model suggests a good overall model fit.

Table 8: Goodness of Fit

Criteria	Estimated Model	Benchmark
SRMR	0.113	< 0.08
d_ULS	0.572	$<HI_{95}=1.74$
d_G	0.238	$<HI_{95}=1.27$
Chi-Square	184.863	
R-squared	0.481	
R-squared adjusted	0.468	

Source: Smart PLS-4 (2025)

4.8 Path Analysis

Figure 2 shows the analysis of the hypothesized paths in this study. The regression results of the path relationships are also specified.

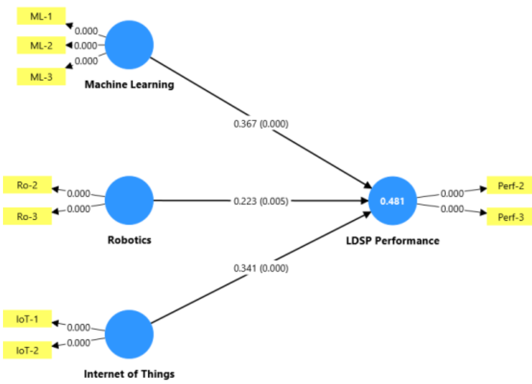

Figure 2: Path Diagram
Source: Smart PLS-4 (2025)

Figure 2 shows that the path coefficient from 'Machine Learning' to 'LDSP Performance' is positive ($\beta1=0.367$), implying a direct relationship. The t-statistics of this path ($t=4.462$), as indicated in Table 5, is significant at the 5% level ($p=0.0$). Therefore, it can be concluded that adopting Machine Learning, as a subset of AI, has directly and significantly improved the achievement of optimized performance at the LDSP.

Similarly, the path coefficient from 'Robotics' to 'LDSP Performance' is positive ($\beta2=0.223$), indicating a direct relationship. Also, the t-statistic of this path ($t=2.798$) as indicated in Table 5 is statistically significant at the 5% level ($p=0.05$). Thus, it is concluded that adopting Robotics as a subset of AI has positively and significantly affected the achievement of optimized performance at the LDSP.

Furthermore, the coefficient of the path from 'Internet of Things' to 'LDSP Performance' is also positive ($\beta3=0.341$), suggesting a direct relationship. In addition, the t-statistic of the path ($t=5.202$) as revealed in Table 9 is significant at the 5% level ($p=0.0$). This implies that adopting the Internet of Things, as a subset of Artificial Intelligence at LDSP, has directly and significantly influenced their achievement of optimized performance.

Table 9 – Path Coefficients

Paths	Beta	Mean	Standard Deviation	T-statistics	P-values
Machine Learning -> LDSP Performance	0.367	0.342	0.066	4.462	0.00
Robotics -> LDSP Performance	0.223	0.374	0.082	2.798	0.05
Internet of Things -> LDSP Performance	0.341	0.226	0.08	5.202	0.00

Source: Smart-PLS 4 (2025)

5.0 Discussion

An incontrovertible fact that is supported by experiential and experimental facts from different milieu is that smart ports can be regarded as the game-changer that addresses the new challenges faced by international trade and logistics systems (Farzadmehr et al, 2023: Du, 2023, Marc, 2023: Xu, 2024: Zhong, 2025: Purani, 2025: Meranda et al, 2025). It is apparent that modern ports now leveraged digital technologies, such as the IoT, robotic-cranes, big data, cloud computing, and ML, and through them increase their capacity for intelligent operation, improve their sustainability ratings and optimized the allocation of resources in port operation (Hopf et al, 2023: Xu, 2024: Kolbjørnsrud, 2024: Zhong, 2025: Purani, 2025: Meranda et al, 2025).

A significant fact unearthed from this study is that the conceptualization, design, and operationalization of the LDSP are done with these realities in mind. This makes the tactical and strategic functionality of LDSP a clear departure from what is obtainable in extant ports in the Nigerian clime. Findings from this study indicated that an overwhelming majority of the respondents (88.8%) affirmed that they are ICT savvy (Table 3), and to support this assertion, 58.4% (Table 4) of the respondents posited that AI tools (machine learning, robotics, internet of things) have improved operational efficiency at the LDSP. This finding is in tandem with a similar report on how the introduction of AI and digital innovation in the ports of Raffina, Los Angeles, and Long Beach (all in the United States of America) has advanced to help promote higher work efficiency (Zhang et al, 2024).

Another primary objective of this study was to examine the nexus between the operationalization of the LDSP as a smart port and the achievement of a reduction in the risk of environmental mismanagement at the port. 62.4% of the respondents enthused that the deployment of AI strongly catalyzed attaining a green port status at the LDSP. Furthermore, 64% of the respondents believed that the LDSP performs better in energy conservation and pollutant emission reduction due to the utilization of AI in its operations. These findings align with the constructions of DIT that indicated that while already established institutions generally struggle with the adoption of new technology, newly built organizations that has their operational architecture design on an AI ecosystem achieve swifter integration of their internal processes, and this usually enhances their performances (Jian et al, 2022).

The results from the SEM of the tested hypotheses affirmed the position that there are elements of causality in the relationships between all of the identified endogenous variables and the achievement of enhanced performance at the LDSP. In specific terms, the result (Figures 1, 2, and Table 9) indicated a statistically significant impact of all the AI subsets of ML, Robotics, and IoT on the enhancement of performance at the LDSP. One of the objectives of this study is to provide an experimental assessment of the confluence between AI and the enhancement of the operational capacity of a new port; this finding thus validated the stated hypothesis. It also affirmed findings from earlier studies in analogous industries indicated that the introduction of AI to the extant industrial ecosystem triggers salient benefits, performance enhancement inclusive (Hopf et al, 2023; Xu, 2024; Kolbjørnsrud, 2024; Zhong, 2025).

However, it is not all ‘cheery news’, as the findings also indicated that less than half of the population of the sampled members of the LDSP workforce (46.4%) agreed that “there are periodic training or capacity building seminars organized by the management of the LDSP for staff to bridge the ICT skill deficiency gaps”. This is a red flag that the management of the LDSP should not ignore. The rapidity of dynamism in the global digital ecosystem requires that staff members be exposed to periodic sessions of capacity enhancement on nascent development in AI.

6.0 Business Contributions and Conclusions

This research is one of the first to empirically assess the confluence between the holistic adoption of AI and the attainment of enhanced operational performance in a newly constructed port. While previous studies on the discourse has provided evidences that the adoption of AI and digital innovations has proven effective in catalyzing positive operational changes in different sectors of the maritime industry(Zaman et al, 2017; Othman et al, 2022; Du, 2023; Ajayi, 2023; Hopf et al, 2023; Kolbjørnsrud, 2024; Xu et al, 2024), studies that examined the primary objectives of this research are relatively short - in-supply. By providing an empirical assessment of the identified endogenous variables on the performance of the LDSP based on the employees' perceptions within the facility, this study created an objective analysis involving key stakeholders of a port facility that are part of the day-to-day running of the facility.

This study also provides an evidence-based result on the intersection between adopting AI in operational characterizations and achieving sustainability within a port facility. While literature established that AI is efficient in the detection and identification of marine environmental pollution as a results of activities in ports (Zare et al, 2025: Ioras and Bandara, 2025), this paper weighed-in on the discourse by affirming that view of the workforce of a newly constructed port facility and its influence on the optimization of vessel routes and port traffic flow, and predictive maintenance to ensure efficient asset use and waste management at the LDSP.

These contributions are pivotal to factual decision-making by the management of the LDSP and ports with similar characteristics, as this will validate their investment goals and provide the necessary impetus to sustain their futuristic investment drive in newer versions of AI architecture as required.

While it is a truism that the construction of AI-driven new seaports is a capital-intensive venture, findings from this study have provided veritable insights into the benefits that are accrued to the investors (in terms of profit), and sustainability ratings (in terms of environmental preservation). Based on this, it is advocated that fresh investment in the design and construction of new ports should endeavor to build 'smart' ports. This will drive the competitiveness of such ports among regional contemporaries and remove the threat of such ports losing out on the benefits of being part of an AI-driven homogenized port system already posing substantial threats to non-smart ports as competitors for maritime business.

7.0 Limitations and Areas of Future Research.

This paper is not without some limitations, one of which is that the choice of the respondents for the study is limited solely to the staff of the LDSP. While perception studies are acceptable for research endeavors, they can sometimes be subjective, particularly when the respondents work within the organization being studied. To this end, future studies that will combine secondary data sourced from government agencies like the Nigeria Port Authority (NPA) with oversight functions on records of port economic activities, and the Nigerian Administration and Safety Agency (NIMASA) with oversight functions on regulating maritime safety and security, and environmental protection. Such a study will provide a deeper insight into the discourse.

Secondly, this study focused on a newly conceptualized AI-driven port; the valid findings may not hold true for extant ports within the study area that adopt digital innovations. Therefore, it is suggested that old ports in the country, like the Apapa, Tin Can, and Onne ports, be subjected to studies investigating the extent of AI adoption in their operations and the successes and challenges being encountered by the management of these ports.

Data Availability Statement: Data used in the research are available

Conflicts of Interest: None

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