Journal of Business Vol. 16, N°2
pp. 155-180
eISSN 2078-9424
doi: 10.21678/jb.2025.2610

Received on February 1, 2024
Accepted on March 15, 2025

Automation, sustainability, and digitalization at the Port of Callao: An exploration of operations at the South Dock from 2019 to 2022

Lesly Graciela Chávez Casimiro
Faculty of Business, Universidad Peruana de Ciencias Aplicadas, Lima, Peru
u201918758@upc.edu.pe

Ron Mesia
Faculty of Business, Florida International University, Miami, United States of America.
rmesia@fiu.edu

Julio Ricardo Moscoso Cuaresma
Faculty of Business, Universidad Peruana de Ciencias Aplicadas, Lima, Peru
julio.moscoso@upc.pe
https://orcid.org/0000-0001-5343-3713

Abstract. This research aims to ascertain the impact of automation and sustainability on operations and the implications of digitalization at the South Dock of the DP World Port of Callao between 2019 and 2022. A two-stage mixed structure methodology with a data envelopment analysis (DEA) model is used to assess the relative efficiency of the decision-making units, while a Tobit regression is employed to compare coefficients to determine the significance of the variables. The results provided a comprehensive insight into the dock's performance, showing that digitalization significantly affected supply chain efficiency and. However, the study also highlighted the importance of addressing challenges related to workers' adaptation to new technologies and effective coordination between different actors involved in managing the port supply chain. Collectively, these results offer a deeper understanding of the beneficial influence of digitalization on port operations, highlighting the significance of policies that promote a smooth transition to digital technology in developing nations like Peru.

Keywords: Automation; port processes; digitalization; data envelopment; Tobit regression.

Automatización, sostenibilidad y digitalización en el Puerto del Callao: Exploración de las operaciones del Muelle Sur durante el período 2019-2022

Esta investigación tiene como objetivo determinar el impacto de la automatización y la sostenibilidad en las operaciones, así como las implicancias de la digitalización en el Muelle Sur del Puerto DP World del Callao entre 2019 y 2022. Se emplea una metodología mixta en dos etapas con un modelo de análisis envolvente de datos (DEA, por sus siglas en inglés) para evaluar la eficiencia relativa de las unidades de toma de decisiones, mientras que se utiliza una regresión Tobit para comparar coeficientes y determinar la significancia de las variables. Los resultados brindaron una visión integral del desempeño del muelle, mostrando que la digitalización tuvo un efecto significativo en la eficiencia de la cadena de suministro. Sin embargo, el estudio también destacó la importancia de abordar los desafíos relacionados con la adaptación de los trabajadores a las nuevas tecnologías y la coordinación efectiva entre los diferentes actores involucrados en la gestión de la cadena logística portuaria. En conjunto, estos resultados ofrecen una comprensión más profunda de la influencia positiva de la digitalización en las operaciones portuarias, subrayando la importancia de políticas que promuevan una transición fluida hacia la tecnología digital en países en desarrollo como el Perú.

Palabras clave: Automatización; procesos portuarios; digitalización; análisis envolvente de datos; regresión Tobit.

1. Introduction

The COVID-19 pandemic has had a significant impact on global maritime performance. This, in turn, caused significant changes in product demand and created new challenges in terms of the security of port operations (Hsu et al., 2023; Othman et al., 2022). Although the level of global trade increased in 2021 (Du, 2023), the rapid rise in cargo volume resulted in a surplus of containers in ports and an inadequate supply for carriers, driving up freight costs (Hsu et al., 2023). The integration of seaports into supply chains has had a positive effect on their performance (Paulauskas et al., 2021), compelling the maritime port industry to initiate digital transformation to improve the efficiency, reliability, and sustainability (González-Cancelas et al., 2020; Jović et al., 2022; Lin et al., 2022) of international freight transportation.

The maritime industry has lagged behind other industries in terms of digitization (Merino et al., 2022). In recognition of this reality, Peru has implemented technology to facilitate the digital transformation of its ports, including through its busiest such facility, the Port of Callao in Lima. Among the actions implemented to date, the Smart Port Callao project, financed by the Inter-American Development Bank and executed by the Valencia Port Foundation, has allowed Callao to introduce various indicators to measure the progress achieved by maritime, port, and port terminal authorities (Autoridad Nacional Portuaria del Perú, 2022). Likewise, training, workshops, system courses, mentoring, and digital governance were provided to National Port Authority (APN) employees, members of the Peru branch of the Women's International Shipping & Trading Association (WISTA Peru), and the general public. The Port of Callao promoted digital adaptation through pilot projects such as TradeLens, a digital system for information exchange between the different actors in maritime trade, as well as the Callao Port Community System (PCS) Master Plan and the Port Management System (PMS) for management and coordination of port operations (APAM PERÚ, 2022). These actions justified the initiatives to implement Peruvian port digitalization, and provided the basis for this research.

In contrast, there has been a global acceleration in port digitization in recent years. As a result, not many ports have adopted cutting-edge technology or digitization (Belmoukari et al., 2023). However, port digitalization has presented significant progress in Latin America, where around 40% of ports have already implemented digital technology, and 25% of ports have started a digitalization process in recent years (COMEX PERÚ, 2021). These figures reflect the importance of technology in the port sector and the interest in taking advantage of its benefits to improve the efficiency and competitiveness of ports.At present, in Peru, projects have been devised to promote digital transformation. For example, as noted above, the Callao Port Community System introduced a Smart Port Callao project, intended for application over five years starting in 2020.

There have been no prior scientific studies on the digitalization of Peruvian ports—even with the launch of the "Smart Port" initiative in the port of Callao—on which this research could draw. As a result, we have incorporated research on the digital transformation of ports in other countries, both developed and developing. Our aim is to better understand the digitization process and the significance of automation, teamwork, and sustainability in the digital transformation of a major South American port.

More specifically, we seek to determine how digitization affected the port processes in the South dDck of the Port of Callao (DPWC-Callao), for which the port authorities set three objectives for 2019 –2022: Objective 1 (O1) concerns the consequences generated by automation; Objective 2 (O2) concerns the results generated by sustainability in port digitalization; and Objective (O3) concerns the values generated by collaboration in safety.

2. Theoretical Framework

Port digitalization

Port digitalization, is the process through which digital technologies are implemented in seaports (Paulauskas et al., 2021). Automation created an incentive for logistics systems to adjust and implement digital technologies when providing their services while constantly striving to remain efficient, profitable, and competitive (Agatić & Kolanović, 2020). Beyond these incentives, digitalization is considered one of the main routes for developing existing ports (Philipp, 2020). The maritime industry, beyond its traditional limits, provided different opportunities to improve logistical productivity, efficiency, and sustainability. This allowed smart ports to adopt modern information technologies to enable better planning and management between ports (Heilig et al., 2017). Global integration and the adoption of digital technologies have generated new challenges and opportunities in intermodal transport logistics in seaports and main connection areas. With the exponential growth in container handling and mega-hub automation, there is a constant need to address new planning challenges through smart software solutions (Faria, 2020).

Port automation is based on the use of automated equipment and processes to replace, totally or partially, the operations carried out by manned terminals (Knatz et al., 2022). Research reveals that ports are currently undergoing a transition from first- to fifth-generation facilities (Belmoukari et al., 2023). This trend (Hong et al., 2023) goes beyond digital transformation, which is applied in semi-automated terminals (González-Cancelas et al., 2020); automated container terminals (ACTs), considered an essential strategy for ensuring improvements to the efficiency, high quality, and sustainability of conventional terminals (Hong et al., 2023; Martín-Soberón et al., 2014; Sun et al., 2023), have in gained popularity over the last decade (Knatz et al., 2022). Because of this, they have attracted a good deal of research (Naeem et al., 2023). However, Knatz et al., 2022 found that only 3% of container terminals worldwide were complete or semi-automated. A crucial factor impeding the implementation of port automation is the considerable initial investment that operators and investors face. It is estimated that the operating costs of a new automated terminal should be 25% lower than a conventional terminal, with 30% higher productivity and 10% lower operating expenses, for this outlay to be justified (López-Bermúdez et al., 2020). Therefore, it is essential to ensure that a long-term plan is in place to ensure innovative development of efficient smart ports (Li et al., 2023).

Port digitalization is vital to the vision of “cyber-physical systems,” which consists of developing a smart port in which port communities, including transporters and shippers, collaborate with robots through human–technology interactions. These systems require a digital platform with the appropriate hardware and software devices to transform real-time data from different sources into meaningful information at intelligent ports. The intention is to help plan, deliver, and execute mobility solutions based on the information created by the Internet of Things (IoT) while helping to connect and automate port equipment (Min, 2022). Some examples of IoT platforms used by ports include PTC ThingWorx, GE Predix, ABB Ability, Siemens MindSphere, and SAP-ERP (Merino et al., 2022). Regardless of type, all platforms are intended to self-configure, self-regulate, and optimize port operations to handle supply chain disruptions and variations in port demand (Min, 2022). Thus, IoT platforms have helped facilitate device management, handle hardware/software communication protocols, collect/analyze data, facilitate data flow, and improve the functionality of intelligent applications.

Sustainability in port digitalization

Sustainable development was introduced to ensure the continuity of resources to maintain and safeguard human life while responding to economic, ecological, and social conditions (Madroñero-Palacios & Guzmán-Hernández, 2018). Accordingly, a sustainable port will implement development strategies and activities in all areas of port operations to enhance its competitiveness while protecting and sustaining three dimensions: environmental, economic, and social aspects (Bergqvist & Monios, 2019; Puig et al., 2020; Vega-Muñoz et al., 2021). Digital innovation has allowed the maritime industry to adopt more environmentally sustainable practices to mitigate its ecological impact on the global supply chain (Othman et al., 2022; Zhang et al., 2024).

Ports that have adopted sustainable practices include Rotterdam and Antwerp, part of the Trans-European Transport Network (TEN-T). Through digital database technologies such as blockchain and the IoT, these ports have sustainable operations that contribute to higher levels of security, process optimization, and sustainability. Consequently, integration technology has made it possible to merge the physical and digital worlds (Philipp, 2020). The case of the Port of Rotterdam illustrates how digitization and advances in information and communications can transform document management and decision-making into a fully electronic format. Here and elsewhere, such improvements have significantly improved the maritime sector's efficiency and reliability in trade and transportation (Sankla & Muangpan, 2022). With digital transformation, port efficiency increased, improving cost control in logistics services, leading to sustainable operation and organization. In addition, this process contributed to environmental protection through energy consumption savings (Hsu et al., 2023).

In the case of integrating technology for sustainability in developing countries, the transition process has faced many challenges. Initially, technology implementation involved creating a network that interconnected all port areas, which meant that stakeholders operating within these areas had to be prepared to migrate to more advanced port systems (Othman et al., 2022). In the beginning there was resistance to change from some employees because more automated processes entailed training and a reduction in roles and responsibilities. Yet for digital integration to become a reality, it was necessary to define guidelines that balanced out the influence and power among government authorities, technology companies, logistics companies, and communities (Chen et al., 2020). To prevent problems between port authorities and the unique challenges posed by data digitization, independent organizations developed a wide range of international standards proposing that port cities adopt appropriate regulatory frameworks (Halff et al., 2019).

Port digitalization security

Security in port digitization refers to the measures and practices implemented to protect the systems and data used in digitizing a port (González-Cancelas et al., 2021). In recent years, various forms of trade, including maritime transportation, have incurred significant costs and damage due to cyberattacks. The geographical reach of goods transportation does not protect the industry, as attacks can be launched almost anywhere there is an internet connection (Melnyk et al., 2022). Therefore, the importance of risk management is increasing as the need to strengthen various aspects of security grows (Pöyhönen, 2023).

Information and communication technology (ICT) systems in port environments generally contain databases that store data related to ships and ports, as well as a terminal operating system (TOS) that performs crucial operations in stowage planning. A comprehensive assessment of all port ICT systems with network interfaces for external connections is required to identify potential vulnerabilities and assess their impact ((Kapalidis et al., 2022; Senarak, 2021; Simola et al., 2023). Considering that an adversary can easily manipulate port operations and the availability of the TOS by exploiting vulnerabilities in the data transmission layer, thorough and rigorous risk assessment and management are vital to safeguard operational integrity (Beaumont, 2018).

Evaluating cyber risk in the maritime domain is a relatively recent concept, and in recent years several countries have emphasized its importance and urgency for the maritime sector (Pöyhönen, 2023). Given that all layers of smart terminals operate interconnectedly and collaboratively to fulfill a specific task, conventional risk assessment approaches prove inadequate in accurately capturing the dynamic complexity of port operations (Progoulakis et al., 2021).

Lastly, it is important to note that the vulnerability of cyberspace and future port systems poses a significant threat to security and the economy as cyberattacks continue to evolve into more sophisticated and difficult to detect forms (de la Peña Zarzuelo, 2021).

Data envelopment analysis

Data envelopment analysis (DEA) is one method used to address the challenges outlined above (Liu et al., 2023). The DEA model proposed by Charnes in 1978 is a tool that evaluates the relative efficiency between different decision-making units (DMUs) with multiple inputs and outputs. Their approach is based on linear programming to calculate the relationship between the inputs and outputs of these DMUs, thus allowing an objective comparison of their performance (Arhin et al., 2023) as well as providing a set of inefficiency scores or estimates (Tsionas, 2023).

In the present study, we propose the use of a DEA-CCR model as a tool to evaluate the efficiency of seaports through the analysis of cross-sectional data in financial reports. This model focuses on inputs and assumes that returns are constant to scale (Nong, 2023). In addition, we employed the variable returns to scale model, known as the Banker, Charnes, and Cooper (BCC-DEA) model (Arhin et al., 2023).

The maximized DEA equation is as follows:

$$h_0 = \frac{\sum_{j=1}^{s} w_{j\,Y_{j0}}}{\sum_{i=1}^{r} v_{i\,X_{i0}}} \tag{1}$$

$$\frac{\sum_{j=1}^{s} w_{j\,Y_{jm}}}{\sum_{i=1}^{r} v_{i\,X_{im}}} \leq 1, m = 1, 2, \ldots, n \tag{2}$$

$$W_j \geq 0; j = 1, 2, \ldots, s \tag{3}$$

$$V_i \geq 0; i = 1, 2, \ldots, r \tag{4}$$

Where,

$Y_{jo} = output\ j\ of\ the\ DMU\ 0;$

$X_{io} = input\ of\ the\ DMU\ 0;$

$W_j = weight\ of\ the\ output\ j;$

$V_j = weight\ of\ the\ input\ i$

$n = No.\ of\ DMU$

$s = No.\ of\ input$

$r = No.\ of\ output$

Tobit regression

We used the Tobit regression model was used to determine the effect of the factors on the efficiency of DEA performance. The DEA efficiency value displayed was between 0 and 1, so we employed binary Tobit regression to calculate the weight of the selected factors used as indicators of smart ports in this study. Using the DEA modeling method, we also factored *n* DMUs into the Tobit regression estimation (Yen et al., 2023). Unlike the linear equation, whose parameters were calculated using the ordinary least squares algorithm, the Tobit regression method, based on maximum truth estimation, is usually used to resolve censored dependent variables (Tobin, 1958).

The model is expressed as follows:

$$Max\ e_k = \frac{\sum_{j}^{t}=1^{v_j Y_{jk}+z_o}}{\sum_{i}^{s}=1^{u_i X_{ik}}} \tag{5}$$

$$s.\,t.\ \frac{\sum_{j}^{t}=1^{v_j Y_{jk}+z_o}}{\sum_{i}^{s}=1^{u_i X_{ik}}} \leq 1, m = 1, 2, \ldots, n \tag{6}$$

$v_i \geq \varepsilon > 0, i = 1, 2, \ldots, s$ (7)
$v_j \geq \varepsilon > 0, j = 1, 2, \ldots, t$ (8)
$y_i = \beta + \Sigma_j \beta_j x_{ij} + \varepsilon i, i = 1, \ldots, n$ (9)

Where,

y_i : *the difference of DEA port model i*;
β : *cons* tan *t e*
β_j : *factor coefficient j*
x_{ij} :*factor j of the port i;*
ε_i : *tér* min *or the port error i.*

3. Methodology

This study, carried out using a mixed approach, seeks to determine the impact of digitalization on the operations of the South Dock of the Port of Callao (DPWL-Callao) during 2019–2022. The study has one general and three specific hypotheses, as follows:

General hypothesis: Digitalization significantly impacted the port processes of the South Dock of the Port of Callao (DPWL-Callao) during 2019–2022.
First specific hypothesis (H1): Automation significantly impacted the port processes of the South Dock of the Port of Callao (DPWL-Callao) during the 2019–2022 period.
Second specific hypothesis (H2): Sustainability significantly impacted the port processes of the South Dock of the Port of Callao (DPWL-Callao) during the 2019–2022 period.
Third specific hypothesis (H3): Security significantly impacted the port processes of the South Dock of the Port of Callao (DPWL-Callao) during the 2019–2022 period.

We assessed the input and output variables were assessed, considering the boarding and unloading values, to test these hypotheses. We subjected the data to a data envelopment analysis (DEA) to evaluate the port's performance, and employed a Tobit regression analysis to measure the efficiency of the port.

Sampling process: size and selection

For this research, we used several monthly and annual indicators from the OSITRAN performance report to evaluate the performance of the South Dock (DPWL-Callao) over the period 2019–2022. Within the report, container traffic flow indicators were used to test the hypotheses.

Several significant limitations were identified in the search for and analysis of information for this research project. On the one hand, OSITRAN provides only limited information about its reports on an annual and not monthly basis, creating difficulties in obtaining the necessary data for the DEA analysis and the Tobit regression. As a result of these data limitations, we had to retrieve the statistical reports of the National Port Authority (APN), in which monthly documentation on port traffic is posted. Finally, for data analysis, we used only the information on the monthly loading and unloading of full containers per month was used, and not that corresponding to the registration of empty containers.

Table 1 presents the dimensions taken as a reference for our methodology. For each indicator, we were able to obtain the concepts and initiatives of productivity, costs, income, and maintenance pertaining to the Port of Callao. The table also specifies the key characteristics for ascertaining the efficiency with which the port operates and what can be improved through digitalization.

Table 1:
Description of evaluation criteria

Dimensions	Indicators	Description	Source
Dimensions	Port crane productivity	Evaluates the number of containers per hour	Port statistics APN (2019–2022)
	Average ship waiting time	Reduces average ship waiting time	Port statistics APN (2019–2022)
Sustainability	Waste management	Reduces or controls spending on solid and oily waste.	South Dock Annual Performance Report – DPWC (2019–2022)
	Fuel cost	Reduces fuel costs due to port operations.	South Dock Annual Performance Report – DPWC (2019–2022)
Security	Number of Accidents	Reduces the number of accidents that occur in the port	South Port Annual Performance Report – DPWC (2019–2022)
	Claims registration	Reduces complaints about paperwork or poor port operations.	South Port Annual Performance Report – DPWC (2019–2022)
Digitization	Income from container monitoring	Maintains or increases income from monitoring containers entering and leaving the dock.	Port statistics APN (2019–2022)
	Application maintenance and support	Uses more digital systems and minimize the use of manuals	South Dock Annual Performance Report – DPWC (2019–2022)

4. Results of the DEA model

To evaluate efficiency performance, we employed DEA) models that focus on inputs, such as CCR and BCC models. Only five port periods were classified as benchmarks, where the efficiency score was equal to 1. These periods were 2019-3, 2020-2, 2021-11, 2022-2, 2022-3, and 2022 -5, whereas the 2021-4 period obtained the lowest efficiency score. As to the ranking scale, most periods are rated with constant returns to scale (CRS). Only two periods with increasing returns to scale (IRS), 2021-7 and 2021-10, were identified.

Table 2
DPWC monthly performance efficiency, 2019-2022

DMU	Efficiency	eff%	lamb sum	rts
2019-1	0.823788515	82.38%	1	Constant
2019-2	0.944617029	94.46%	1	Constant
2019-3	1	100.00%	1	Constant
2019-4	0.751859648	75.19%	1	Constant
2019-5	0.624876008	62.49%	1	Constant
2019-6	0.706773258	70.68%	1	Constant
2019-7	0.699210439	69.92%	1	Constant
2019-8	0.739492888	73.95%	1	Constant
2019-9	0.675096127	67.51%	1	Constant
2019-10	0.735094182	73.51%	1	Constant
2019-11	0.709344267	70.93%	1	Constant
2019-12	0.783728595	78.37%	1	Constant
2020-1	0.666554726	66.66%	1	Constant
2020-2	1	100.00%	1	Constant
2020-3	0.979591837	97.96%	1	Constant
2020-4	0.668806391	66.88%	1	Constant
2020-5	0.602445828	60.24%	1	Constant
2020-6	0.88594829	88.59%	1	Constant
2020-7	0.650665786	65.07%	1	Constant
2020-8	0.807440962	80.74%	1	Constant
2020-9	0.754014002	75.40%	1	Constant
2020-10	0.803036948	80.30%	1	Constant
2020-11	0.623078946	62.31%	1	Constant
2020-12	0.562363501	56.24%	1	Constant
2021-1	0.503693153	50.37%	1	Constant

2021-2	0.736196319	73.62%	1	Constant
2021-3	0.920245399	92.02%	1	Constant
2021-4	0.471861556	47.19%	1	Constant
2021-5	0.525854514	52.59%	1	Constant
2021-6	0.522473594	52.25%	1	Constant
2021-7	0.577221917	57.72%	0.99999	Increasing
2021-8	0.612694274	61.27%	1	Constant
2021-9	0.807587675	80.76%	1	Constant
2021-10	0.873271024	87.33%	0.99999	Increasing
2021-11	1	100.00%	1	Constant
2021-12	0.683796976	68.38%	1	Constant
2022-1	0.863844396	86.38%	1	Constant
2022-2	1	100.00%	1	Constant
2022-3	1	100.00%	1	Constant
2022-4	0.819731425	81.97%	1	Constant
2022-5	1	100.00%	1	Constant
2022-6	0.856100082	85.61%	1	Constant
2022-7	0.884996675	88.50%	1	Constant
2022-8	0.976702368	97.67%	1	Constant
2022-9	0.993710436	99.37%	1	Constant
2022-10	0.990569653	99.06%	1	Constant
2022-11	0.914104816	91.41%	1	Constant
2022-12	0.813828975	81.38%	1	Constant

5. Result of the Tobit regression model

Table 3 presents the results obtained using the Tobit regression model, which allows a direct comparison of the importance of the variables in examining the coefficients. In the case of sustainability, only the “waste management” variable was found to have a significant and negative influence on efficiency. this may be due to the need to incur higher investment costs, such as the proper treatment of waste, its transportation, and the implementation of recycling systems.

Table 3
Tobit regression results

Variables	Original model	
	coefficient	p value
Productivity of port cranes container/hrs.	0.011447	0.000
Average ship waiting time (hrs.)	0.0024556	0.850
Waste management (TN)	-0,0002899	0.765
Fuel Cost (miles $)	1.786.063	0.000
Number. of accidents	2.205.811	0.000

6. Discussion

To investigate the impact of digitalization on the port processes of the South Dock of the Port of Callao (DPWC-Callao) during 2019–2022, we used two methods. First, we developed a Tobit model, which allowed us to obtain results from a sampling of scales of the sustainability coefficients. This showed that the "waste management" variable presents significant and negative performance in efficiency. This is due to the scarcity of incurring higher investment costs, transportation, and the implementation of recycling systems. Second, we developed the DEA model, which studied and determined the efficiency of five operating periods at the port, classified in order to compare efficiency significantly. Through this procedure, we found that the 2021-4 period obtained an efficiency score lower than other periods.

The methods used allowed us to determine the coefficient scale between both models. The DEA model generally showed better results regarding than the Tobit regression. It is worth mentioning that the standardized indices allowed us to compare the relative effects of the indicators used across the model. We classified and ordered the impacts on port efficiencies, finding that they played a significant but varying role in the indicators and relationship terms. If the results of the coefficient indicators were negative, they would manifest as the lowest priority aspects of development of the smart port.

The port digitalization indicator has been a relevant topic in recent years, with the implementation of digital technologies that have transformed the operation and management of seaports. Paulauskas et al., 2021 highlighted that digitalization has become one of the main directions of development of current ports, largely because the maritime industry has provided numerous opportunities to improve logistics productivity, efficiency, and sustainability.

The adoption of digital technologies in seaports has been driven by automation and the need to adjust to logistics systems constantly striving for efficiency and competitiveness (Agatić & Kolanović, 2020). This has enabled digital transformation in smart ports through incorporation of modern information technologies to improve planning and management within and between ports (Heilig et al., 2017). New challenges and opportunities have arisen in intermodal transport logistics in seaports and main connection areas. For instance, exponential container handling and automation growth has occurred, with planning challenges addressed through intelligent software solutions (Kress et al., 2018). However, despite technological advances, only 3% of container terminals worldwide are fully or semi-automated—something that can be attributed to factors such as the influence of operators and investors and the need for considerable initial investment (Knatz et al., 2022). Thus, it is important to note that port digitalization is about implementing technologies and having a long-term plan that encourages innovative solutions for developing smart ports (Liu et al., 2023). The process involves considering aspects beyond automation, such as connectivity, cybersecurity, and environmental sustainability. Furthermore, as López-Bermúdez et al. (2020) have pointed out, the operating costs of a new automated terminal should be 25% lower than for a conventional terminal.

The automation dimension, for its part, positively impacted port performance. Automation in container terminals improves efficiency and quality and provides greater sustainability inn comparison to conventional terminals. Several studies support this finding (Hong et al., 2023; Martín-Soberón et al., 2014; Naeem et al., 2023; Sun et al., 2023). As evidenced in Table 3, the other two indicators of automation, "productivity of gantry cranes" and "average stay time of ships," also have a positive impact. Port congestion is avoided when efficient gantry cranes can handle more containers in less time. Advanced crane technology, such as automated control and monitoring systems, can significantly improve performance and efficiency (Autoridad Nacional Portuaria del Perú, 2022). A shorter average stay time for ships in the port allows for greater punctuality in the delivery of goods; this allows ports to receive products more quickly and reliably, improving customer satisfaction and strengthening business relationships. In a port, this indicator can be affected by the efficiency of port operations, the capacity, and availability of infrastructure, customs processes, and documentation, as well as the coordination and communication between the different port actors (APAM Peru, 2022; Autoridad Nacional Portuaria del Perú, 2022; COMEX PERÚ, 2021).

For the sustainability dimension, the result was a positive impact on fuel costs. As Table 3 shows, this variable was one of the most significant for the dimension, because sustainability was enabled through digitalization and the incorporation of technology that helps the environment (Madroñero-Palacios & Guzmán-Hernández, 2018; Sankla & Muangpan, 2022). The United Nations Sustainable Development Goals supports the International Maritime Organization in promoting technology that optimizes port exercises, labor, and the environment, using better technologies that help reduce carbon emissions, waste management, water use efficiency, and so on. This has encouraged port executives to invest in these technologies to improve port efficiency and met their needs and demands in the current climate. The second variable, waste management, harmed digitalization. This is because the company must make more significant investments in machinery that helps treat waste, transportation, and delays.

Finally, the safety dimension was found to have a positive impact on the number of accidents. This variable was the one that had the most significant effect on the port's digitalization, as seen in Table 3. Fortunately, the port has not faced severe accidents that resulted in death. The accidents that occurred in the Port of Callao were related to machinery operation. The significant influence of digitalization on this variable, accident numbers, came about because operations are now carried out online through operational digitalization and the incorporation of cutting-edge technologies, which has eliminated some jobs. These losses offer advantages in reduced salary costs and increased port efficiency due to faster processes. The second variable in the security dimension, number of claims processed, negatively affected digitalization. This result may be due to the investment cost that the company would incur in developing more interconnected systems with faster data updates to address errors in documentation, the main source of complaint.

7. Conclusions and recommendations

Implementing advanced technologies in port processes, such as automated port cranes, has improved productivity and efficiency in the port of Callao. Reducing vessel waiting times has improved customer satisfaction and business relationships, highlighting the importance of solid infrastructure and fluid communication between port stakeholders in maximizing these benefits. The gradual and selective implementation of automation has proven effective in improving the competitiveness and responsiveness of the Port of Callao in the maritime industry.

Moreover, digitalization has proven to be a valuable resource in improving the safety and work efficiency of port processes. Despite the challenges associated with costs and technological upgrades, implementing digital solutions has led to safer and more productive work environments. Effective management of these challenges can result in an overall improvement in efficiency, competitiveness, and innovation within the port. The adoption of digital technologies in waste management, however, has had mixed impacts on the sustainability indicators of the port of Callao. While implementing digital solutions has promoted more sustainable practices aligned with the Sustainable Development Goals, it has also posed additional challenges, such as increased operating costs, particularly of fuel consumption. Decision-makers must conduct thorough studies and prioritize investment in the digital technologies most pertinent to and advantageous for the port's circumstances to strike a balance between operational efficiency and environmental sustainability.

The findings of this study highlight the importance of adopting strategic and data-driven approaches to implementing digital technologies in the port environment. The study emphasizes the need to consider operational efficiency and social and environmental impacts when implementing digital solutions in the Port of Callao to improve competitiveness and long-term sustainability. In this regard, we recommend that the port continue to invest in the integration of digital technologies into its operations since this has the potential to significantly enhance productivity, efficiency, and competitiveness. It is important to note that the automation of port procedures is associated with the application of sophisticated control and monitoring systems, which enable streamlined operations and reduced wait times, leading to increased effectiveness in the handling of cargo. Similarly, we advise the formulation of a long-term strategy that encourages conversion to a smart port. Important factors, including environmental sustainability, cybersecurity, and connectivity, must be considered in this design. Resource-optimized technology implementation can enhance a port's operational effectiveness and environmental responsibility by reducing carbon emissions and improving waste management.

In conclusion, recent technological advancements have proven essential for the modernization of the Port of Callao, enabling improvements in operational efficiency, time reduction, and fuel consumption. The implementation of digital and automated solutions has demonstrated its impact on the port's sustainability, aligning with global trends in logistics development. In this context, future research should examine how these experiences can serve as a reference for the evolution of the newly developed Port of Chancay, considering the need for gradual and adaptive technological implementation that meets the demands of international trade.

The launch of operations at the Port of Chancay represents a unique opportunity to assess sustainability and efficiency in port management from a long-term perspective. Future studies could focus on how the integration of advanced technologies at this facility can enhance the competitiveness of Peru's port system and alleviate congestion at Callao. Moreover, it will be essential to investigate the impact of these innovations on emission reductions and resource efficiency, ensuring that automation at Chancay develops strategically and progressively to strengthen the port's role in the global trade and logistics network. These findings should be used alongside other indicators—such as energy management, artificial intelligence, remote control, and communication technologies—in future studies on port digitalization in Peru. The study could also serve as a basis for analyzing international ports setting out on their digital transformation process.

Finally, it is important to recall that the applicability of the models employed, coupled with the overall quality of the input data, may have had significant impacts on the results. Consequently, any researcher must consider this study as a foundation while also acknowledging its limitations when interpreting findings and drawing conclusions. Notwithstanding these constraints, this research has yielded valuable recommendations that can support expertise and specialization, as well as informing decision-makers overseeing the Port of Callao in fully leveraging the benefits of digitalization as a key component of the fourth industrial revolution.

Funding:

This research was not supported by external funding.

Disclosure statement

All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

Authors Contributions

Conceptualisation: L.G.C.C..; J.R.M.C.; Methodology: L.G.C.C..; J.R.M.C.; Validation: L.G.C.C..; J.R.M.C.; R.M.; Formal analysis: L.G.C.C..; J.R.M.C.; R.M..; Investigation: L.G.C.C..; J.R.M.C.; Resource: J.R.M.C.; Data curation: L.G.C.C..; J.R.M.C.; R.M.; Writing (Original draft): L.G.C.C..; J.R.M.C.; Writing & Review editing: L.G.C.C..; J.R.M.C.; R.M..; Visualization: L.G.C.C..; J.R.M.C.; R.M.; Supervision: J.R.M.C.; Project administration: J.R.M.C.; Funding acquisition: J.R.M.C.

Data availability statement

All data generated or analyzed during this study are included in this published article.

Acknowledgements

The authors acknowledge the Research Directorate of the Universidad Peruana de Ciencias Aplicadas for funding this project.

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Appendix 1: DPWC Entry and Exit

Period	Container monitoring income (thousands of USD)	Application maintenance and support (thousands of USD)	Productivity of container gantry cranes/hrs
2019-1	560.53	191	30
2019-2	478.03	60	29
2019-3	461.76	48	30
2019-4	673.07	96	31
2019-5	738.96	84	30
2019-6	653.33	108	30
2019-7	645.80	96	29
2019-8	684.33	131	31
2019-9	683.99	84	30
2019-10	700.25	72	31
2019-11	650.97	84	30
2019-12	576.16	143	29
2020-1	677.44	197	29
2020-2	441.34	62	28
2020-3	575.20	49	29
2020-4	659.90	99	27
2020-5	757.25	86	28
2020-6	498.16	111	27
2020-7	678.30	99	26
2020-8	546.60	136	27
2020-9	585.33	86	27
2020-10	554.27	74	25
2020-11	728.02	86	26
2020-12	784.80	148	26
2021-1	876.22	209	24
2021-2	976.73	65	24
2021-3	897.04	52	25
2021-4	978.59	104	30
2021-5	971.84	91	30
2021-6	968.58	117	31
2021-7	965.14	104	32
2021-8	898.25	143	32
2021-9	986.88	91	36

2021-10	940.45	78	36
2021-11	1083.75	91	37
2021-12	1063.98	156	36
2022-1	842.22	219	36
2022-2	822.73	68	36
2022-3	871.04	55	35
2022-4	833.50	110	35
2022-5	771.84	96	37
2022-6	901.58	123	37
2022-7	872.14	110	37
2022-8	790.25	151	37
2022-9	816.88	96	37
2022-10	770.45	82	36
2022-11	802.75	96	36
2022-12	893.98	164	36

Annex 2: DPWC Data

Period	Productivity of container gantry cranes/hrs	Average vessel dwell time (hrs)	Fuel Cost (thousands of USD)	Waste Management (MT)	Number of accidents	Number of processed claims
2019-1	30	19	420	446	3	0
2019-2	29	20.1	131	139	2	1
2019-3	30	19.4	105	112	4	1
2019-4	31	18.1	210	223	2	0
2019-5	30	17.4	184	195	1	2
2019-6	30	17.5	236	251	0	3
2019-7	29	19.3	210	223	0	9
2019-8	31	17.2	289	307	2	3
2019-9	30	17.2	184	195	1	1
2019-10	31	16.3	158	167	3	1
2019-11	30	17.5	184	195	1	4
2019-12	29	17.3	315	335	1	5
2020-1	29	18.1	330	395	2	0
2020-2	28	19.5	103	123	2	0
2020-3	29	18.2	82	99	1	0
2020-4	27	24.4	165	197	3	0
2020-5	28	20.3	144	173	0	0
2020-6	27	20.5	185	222	0	2
2020-7	26	23.3	165	197	3	1
2020-8	27	19.2	227	271	4	1
2020-9	27	19.6	144	173	1	2
2020-10	25	21.6	124	148	2	0
2020-11	26	21.3	144	173	2	2
2020-12	26	20.5	247	296	0	0
2021-1	24	21.5	465	344	2	0
2021-2	24	23.2	145	107	1	0
2021-3	25	20.4	116	86	1	1
2021-4	30	23.3	233	172	2	0
2021-5	30	24.2	204	150	0	0
2021-6	31	23.2	262	193	3	0
2021-7	32	21.3	233	172	3	1
2021-8	32	23.3	320	236	2	3

2021-9	36	21.1	204	150	2	1
2021-10	36	20.5	175	129	1	2
2021-11	37	19.4	204	150	2	1
2021-12	36	21.1	349	258	2	1
2022-1	36	20.3	559	309	1	0
2022-2	36	21.6	175	97	2	3
2022-3	35	23	140	77	1	4
2022-4	35	20.4	279	155	1	0
2022-5	37	20.1	244	135	0	3
2022-6	37	20.1	314	174	3	1
2022-7	37	18.4	279	155	4	6
2022-8	37	18.2	384	213	2	0
2022-9	37	19.1	244	135	1	0
2022-10	36	19.1	209	116	2	0
2022-11	36	19.3	244	135	3	0
2022-12	36	19.3	419	232	2	0