

Smart Port Framework Using Digital Transformation for Efficiency and Transparency of Indonesian Port Services

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ABSTRACT

This study was motivated by the urgency of accelerating digital transformation in Indonesian ports to improve the competitiveness of national logistics, which is still lagging behind according to the 2023 Logistics Performance Index report. The state of the art of this study lies in the development of a Smart Port Optimization Model that simultaneously tests the influence of digital transformation on the efficiency and transparency of port services. This model fills the gap in previous research, which generally examined efficiency alone or was descriptive in nature. The purpose of this study is to formulate and test an empirical model based on digital transformation that can improve the speed, accuracy, cost savings, and openness of service information. The method used is an associative quantitative survey with 200 respondents who are users of three major ports on the island of Java. The analysis was conducted using Structural Equation Modeling–Partial Least Squares (SEM-PLS) to test the validity, reliability, and causal relationships between variables. The results show that port digital transformation has a very strong and significant positive effect on port service efficiency ($\beta = 0.938$; $R^2 = 0.881$) and transparency ($\beta = 0.952$; $R^2 = 0.907$). These findings produced a new empirical model of Smart Port Optimization that integrates the use of information technology, automation, system interconnection, and digital platform innovation into a single tested causal framework. This model can be used as a reference for policy and practice in smart port management in Indonesia and in maritime regions with similar characteristics.

Keywords: smart port, digital transformation, efficiency, transparency, SEM-PLS, port management

INTRODUCTION

As an archipelagic country, Indonesia is highly dependent on port performance to maintain the smooth flow of logistics distribution and international trade. However, the 2023 Logistics Performance Index (LPI) report shows that Indonesia's ranking has dropped from 46th (2018) to 63rd (2023), indicating a decline in logistics efficiency, particularly in the port clearance and digital technology integration sectors [1]. This condition emphasizes the importance of digital transformation in accelerating port modernization, considering that ports are vital nodes in the global supply chain [2].

At the global level, developed countries such as China, South Korea, and Singapore have implemented smart ports based on the Internet of Things (IoT), Big Data, and Artificial Intelligence (AI), which have been proven to increase service efficiency by up to 40% [3]. Meanwhile, Indonesia has only just begun to adopt digital systems such as Inaportnet, Indonesia National Single Window (INSW), and IPC Online System, which are still partial and fragmented [4]. The disparity in digital infrastructure between ports also leads to unequal service quality [5].

The Smart Port concept is believed to be a strategic solution to improve efficiency and transparency. The implementation of smart ports emphasizes the integration of digital technology with the principles of sustainability and accountable governance, thereby reducing logistics costs, decreasing ship waiting times, and improving the reliability of service information.[6] However, in-depth studies linking smart ports with indicators of efficiency and transparency simultaneously in Indonesia are still very limited.

Previous studies have examined port digitalization, such as the use of Big Data and IoT [NO_PRINTED_FORM] [3] or the evaluation of the Inaportnet system [7]. However, most of these studies are descriptive or local case studies, without building causal models that examine the combined effects of digital transformation on efficiency and transparency. This incompleteness creates a theoretical and practical gap that needs to be bridged.

Another limitation is evident in port performance measurements, which generally only focus on aspects of efficiency, such as turnaround time or cargo dwell time [8], and do not give much weight to the dimension of service transparency. In fact, public governance literature emphasizes the importance of information disclosure and auditability to build trust and prevent corrupt practices. This shows that the integration of efficiency and transparency remains a promising area of research.

This study responds to this gap, aiming to formulate and test a Smart Port Optimization Model based on digital transformation that empirically links the impact of digitalization on the efficiency and transparency of Indonesian port services. This model is tested using the Structural Equation Modeling–Partial Least Squares (SEM-PLS) method, which is suitable for testing causal relationships between latent variables [9]. This approach is expected to produce stronger quantitative evidence than conceptual studies alone.

This study focuses on designing and testing a Smart Port Optimization Model based on digital transformation to improve operational efficiency and transparency of port services in Indonesia through empirical SEM-PLS analysis that combines port performance indicators and digital governance principles. This statement confirms the orientation of the study to address the limitations of previous research while providing tangible theoretical and practical contributions.

This research offers novelty in the state of the art it carries, including integrating two outcomes, efficiency and transparency, which have often been studied separately. The researchers use the context of Indonesia as an archipelagic country with diverse port characteristics that present unique complexities rarely discussed in international literature. This study utilizes the latest indicators, including digital traceability and real-time monitoring, which are in line with the latest developments in smart port theory [10], [11].

Furthermore, the proposed model makes an original contribution to port management and digital governance theory. By linking digital transformation, efficiency, and transparency within a causal framework, this article adds a new perspective to the theory of the relationship between technological innovation and public service performance [12]. This model also offers an applicable policy blueprint for governments and port operators to realize efficient, accountable, and environmentally friendly smart ports.

In practical terms, the findings of this study are expected to serve as a basis for stakeholders in designing a roadmap for the implementation of a national smart port. The integration of empirically tested efficiency and transparency indicators will help formulate clearer service standards, accelerate the digitization process, and increase public trust in port services [13]. This research presents scientific originality through an integrative approach that combines digital transformation, efficiency, and transparency of port services. Its originality lies in the construction of an empirical model that is based on the Indonesian context and is globally relevant, contributing new to science in the literature on port management and smart ports.

RESEARCH METHODS

Through explanatory research, the study explains the influence of digital transformation on operational efficiency and port service transparency [14], [15].

The research locations include several strategic ports on the island of Java that represent the highest level of logistics activity in Indonesia, taking into account the level of digitization, volume of goods flow, and diversity of infrastructure [1], [5]. The selection of these locations is relevant to the geographical characteristics of Indonesia as an archipelagic country that faces challenges and opportunities in implementing smart ports.

The research population includes port service users such as exporters, importers, logistics operators, and port staff. Respondents were selected purposively based on criteria of at least one year of experience and having used digital systems such as Inaportnet or INSW. The minimum sample size of 200 respondents followed the recommendations of Structural Equation Modeling–Partial Least Squares (SEM-PLS) analysis, which is 5–10 times the number of indicators [16].

The research instrument was a 1–5 Likert scale questionnaire, developed from the theoretical indicators of each variable. Digital transformation was measured through system integration, process automation, and the use of real-time data analytics [3], [4]. Service efficiency includes service speed, reduction in logistics costs, and ship waiting time [7], while transparency includes cost disclosure, clarity of procedures, and ease of access to information [10]. The instrument was developed following the stages of literature review, expert validation, and testing in accordance with the principles of scale development [17].

The research was conducted in nine stages, starting from preliminary studies, hypothesis formulation, instrument validation, to data analysis using SEM-PLS with SmartPLS software. The analysis included an outer model for validity and reliability, as well as an inner model for the relationship between latent variables, with a loading factor benchmark of > 0.6 , Average Variance Extracted (AVE) > 0.5 , and Composite Reliability > 0.7 . Construct validity and internal reliability were tested using factor loading values and Cronbach's Alpha of at least 0.7 [16], [17]. Data collection was conducted ethically through informed consent and assurance of respondent confidentiality. With this systematic method, the study is expected to contribute scientifically and practically to the development of port services in Indonesia.

RESULT AND DISCUSSION

Respondent Characteristics

This study involved 200 respondents from three major ports on the island of Java that have implemented service digitization, namely Tanjung Priok Port (Jakarta), Tanjung Emas Port (Semarang), and Tanjung Perak Port (Surabaya).

Table 1. Respondent Characteristics

Characteristics	Number of Respondents	Percentage
Gender		
Male	134	67
Female	66	33.0
Age		
< 25 years	71	35.5
26–35 years	83	41.5
36–45 years old	43	21.5
> 45 years old	3	1.5
Position/Occupation		
Manager/Leader	26	13
Assistant Manager	4	2
HR	28	14.0
Administrative Staff	78	39.0
Auditor	3	1.5
Call Center & Customer Service	20	10
Teacher	1	0.5
Student	3	1.5
Helper	2	1.0
Marketing	2	1.0
Operator	12	6.0
Entrepreneur	2	1.0
Specialist	1	0.5
Analyst	5	2.5
Supervisor	13	6.5

Type of Service Accessed		
Loading and Unloading Goods	51	25.5
Digital Services	65	32.5
Document Management	49	24.5
Others (Ports, etc.)	35	17.5
Total	200	100.0

Source: Processed Data Results with SEM-PLS, 2025

In general, the characteristics of respondents show a port workforce profile that is predominantly male (67%) compared to female (33%), reflecting a maritime employment pattern that is still masculine but beginning to show more balanced gender participation. In terms of age, the majority of respondents were in the productive 26–35 age group (41.5%), followed by those under 25 (35.5%), 36–45 (21.5%), and over 45 (1.5%). This composition confirms that port digitalization is supported by young workers who are adaptive to technological innovation, an important factor in the development of smart ports.

In terms of job position, the majority of respondents were administrative staff (39%), followed by HRD (14%), managers/leaders (13%), and customer service (10%). This indicates the dominance of data management and document coordination functions as crucial parts of port operational digitization. Based on the type of service, respondents interacted most with port services (32.5%), loading and unloading of goods (25.5%), document management (24.5%), and digital services (17.5%).

Overall, the respondent profile reflects the readiness of young human resources to face the acceleration of port digital transformation, with a dominant role in administrative activities and core services that form the main foundation for efficient and transparent port services [1], [5].

Respondent Assessment

Respondents' assessment of port digital transformation variables shows positive results in various measurement dimensions.

Table 2. Assessment of Port Digital Transformation Dimensions

Port Digital Transformation	Score	Frequency	Percentage
Use of Information Technology			
Poor	4-6	27	13.5
Fair	7-8	50	25.00
Good	9-10	123	61.50
Service Automation			
Not Good	4-6	24	12.00
Fair	7-8	54	27.00
Good	9-10	122	61.00
Service Digitalization			
Poor	4-6	27	13.5
Fair	7-8	56	28.00
Good	9-10	117	58.50
Service Interconnection			
Poor	4-6	27	13.50
Fair	7-8	56	28.00
Good	9-10	117	58.50
Digital Platform Innovation			
Not Good	4-6	15	7.5
Fair	7-8	70	35.00
Good	9-10	115	57.50

Port Digital Transformation	Score	Frequency	Percentage
Total		200	100.00

Source: Processed Data Results with SEM-PLS, 2025

Most respondents rated the implementation of information technology (61.5%) and service automation (61%) as "good," indicating that port operations have been largely automated. The dimensions of service digitization and system interconnectivity were also rated positively (58.5% good), showing that inter-process connectivity is already in place, although there is still a need to evenly distribute technology implementation across all units. Digital platform innovation received a 57.5% "good" rating, confirming the development of real-time-based services that support ease of user access.

Table 3. Port Digital Transformation Assessment

Port Digital Transformation	Score	Frequency	Percentage
Poor	20–30	21	10.5
Fair	31–40	52	26.00
Good	41–50	127	63.50
Total		200	100.00

Source: Processed Data Results with SEM-PLS, 2025

Overall, 63.5% of respondents rated the port's digital transformation as "good", 26% as "fairly good," and only 10.5% as "poor." These results indicate that digital system integration is sufficiently mature and supports the efficiency and transparency of port services. The "fairly good" proportion indicates the need for network optimization and equalization of technology quality between units, while the small "poor" category shows that digitalization barriers are not yet systemic [1], [5].

Furthermore, the assessment results for the port service efficiency variable also show a positive trend across all dimensions.

Table 4. Assessment of Port Service Efficiency Dimensions

Port Digital Transformation	Score	Frequency	Percentage
Service Speed			
Poor	4-6	27	13.5
Fair	7-8	58	29.00
Good	9-10	115	57.50
Operational Schedule Accuracy			
Poor	4	19	9.50
Fair	7-8	70	35.00
Good	9-10	111	55.50
Reduction in Ship Waiting Time			
Not Good	4	34	17.00
Fair	7-8	60	30.00
Good	9-10	106	53.00
Logistics Cost Savings			
Not Good	4-6	29	14.50
Fair	7-8	62	31.00
Good	9-10	109	54.50
Digital System Integration			
Poor	4-6	25	12.50
Fair	7-8	69	34.50
Good	9-10	106	53.00
Total		200	100.00

Source: Processed Data Results with SEM-PLS, 2025

A total of 57.5% of respondents rated the speed of service as "good" and 55.5% rated the accuracy of operational schedules as "good," indicating an improvement in service reliability. The dimensions of reduced ship waiting times (53% good) and logistics cost savings (54.5% good) indicate the real impact of digitization on operational efficiency. Digital system integration was also rated positively (53% good), although inter-agency coordination needs to be improved to maximize the effectiveness of the system.

Table 5. Port Service Efficiency Assessment

Port Digital Transformation	Score	Frequency	Percentage
Poor	20–30	23	11.5
Fair	31–40	58	29.00
Good	41–50	119	59.50
Total		200	100.00

Source: Processed Data Results with SEM-PLS, 2025

Overall, 59.5% of respondents rated port services as efficient, 29% as fairly efficient, and only 11.5% as inefficient. The dominance of the "efficient" category indicates the success of digital transformation in improving speed, accuracy, and logistics cost savings. This composition confirms that port service efficiency is at a competitive level and supports the development of nationally and globally competitive smart ports [1], [5].

Table 6. Assessment of Port Service Transparency Dimensions

Port Digital Transformation	Score	Frequency	Percentage
Service Availability			
Poor	4-6	27	13.5
Fair	7-8	53	26.50
Good	9-10	120	60.00
Availability of Procedures and Rates			
Poor	4-6	29	14.50
Fair	7-8	59	29.50
Good	9-10	112	56.00
Digital Reporting System			
Not Good	4-6	31	15.50
Fair	7-8	55	27.50
Good	9-10	114	57.00
Service Audit Trail			
Poor	4-6	22	11
Fair	7-8	68	34.00
Good	9-10	110	55.00
User Participation			
Poor	4-6	29	14.50
Fairly Good	7-8	59	29.50
Good	9-10	112	56.00
Total		200	100.00

Source: Processed Data Results with SEM-PLS, 2025

Most respondents (59%) rated port services as "transparent," 29.5% as "fairly transparent," and only 11.5% as "not very transparent." These findings indicate that information disclosure, procedural clarity, and service data access are functioning well thanks to the implementation of digital systems. However, the fact that some respondents rated the services as "fairly transparent" indicates a need for improved consistency in real-time data integration and system integration between service units. The small proportion of respondents who rated the services as "less transparent" indicates that the obstacles are partial and not systemic in nature.

Table 7. Port Service Transparency Assessment

Port Digital Transformation	Score	Frequency	Percentage
Poor	20–30	23	11.5
Fair	31–40	59	29.50
Good	41–50	117	59.00
Total		200	100.00

Source: Processed Data Results with SEM-PLS, 2025

Overall, the analysis results show that 59% of respondents rated port services as transparent, 29.5% as fairly transparent, and 11.5% as less transparent. These findings confirm that digitization and the implementation of the smart port concept have improved accountability and public information disclosure in the port sector. The proportion of "fairly transparent" responses indicates room for improvement in terms of real-time data integration on costs and cargo status, so that the perception of transparency can be felt evenly across all service lines.

In general, these results confirm that digital transformation plays an important role in strengthening transparency and stakeholder trust, while also boosting the competitiveness of Indonesian ports at the national and global levels [1], [5].

Instrument Test Results

The results of testing the research instrument using Structural Equation Modeling–Partial Least Squares (SEM-PLS) show excellent measurement model quality and meet all validity and reliability criteria.

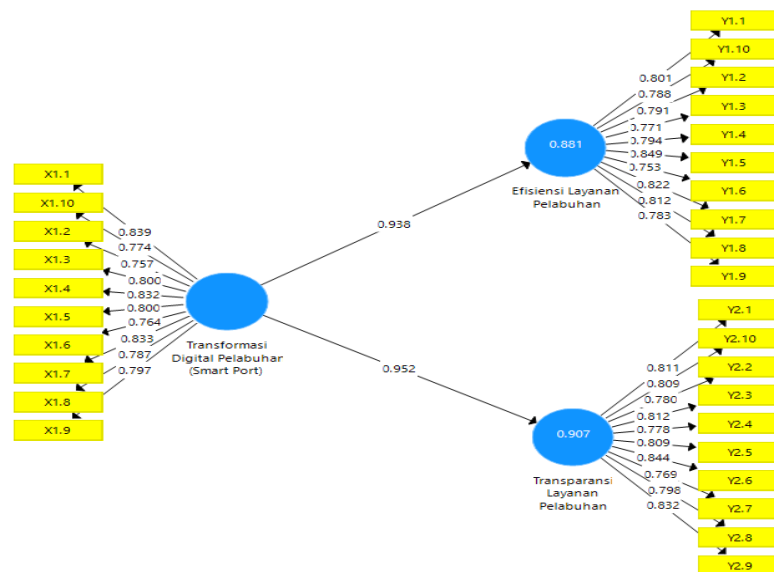


Figure 1. Research Model Algorithm Test Results with SEM-PLS Source: Processed Data Results with SEM-PLS, 2025

Table 8. Outer Loading Results

Indicator	Port Service Efficiency	Port Digital Transformation (Smart Port)	Port Service Transparency
X1.1		0.839	
X1.2		0.774	
X1.3		0.757	
X1.4		0.800	
X1.5		0.832	
X1.6		0.800	

Indicator	Port Service Efficiency	Port Digital Transformation (Smart Port)	Port Service Transparency
X1.7		0.833	
X1.8		0.787	
X1.9		0.797	
Y1.1	0.801		
Y1.2	0.791		
Y1.3	0.771		
Y1.4	0.794		
Y1.5	0.849		
Y1.6	0.753		
Y1.7	0.822		
Y1.8	0.812		
Y1.9	0.783		
Y1.10	0.758		
Y2.1			0.811
Y2.2			0.809
Y2.3			0.780
Y2.4			0.812
Y2.5			0.778
Y2.6			0.809
Y2.7			0.844
Y2.8			0.769
Y2.9			0.798
Y2.10			0.832

Source: Processed Data Results with SEM-PLS, 2025

All indicators in the Port Digital Transformation (Smart Port) construct have loading factors above 0.75 (range 0.757–0.839), indicating strong internal consistency and convergent validity. A similar pattern is observed in the Port Service Efficiency and Port Service Transparency constructs, which also recorded loading factor values above 0.75 [16].

The path coefficient analysis results show a significant positive effect: Port Digital Transformation has a direct effect on Port Service Efficiency with a coefficient of 0.938, and on Port Service Transparency with a coefficient of 0.952. These values indicate that the higher the level of digital transformation implementation, the greater the increase in service efficiency and transparency felt by users.

Table 9. Instrument Reliability Test

Variable	Cronbach's Alpha	rho_A	Composite Reliability	Average Variance Extracted (AVE)
Port Service Efficiency	0.936	0.937	0.946	0.635
Port Digital Transformation (Smart Port)	0.937	0.938	0.946	0.638
Port Service Transparency	0.939	0.940	0.948	0.647

Source: Processed Data Results with SEM-PLS, 2025

The results of Construct Reliability and Validity testing show that all constructs meet high reliability standards. Cronbach's Alpha and rho_A values for the three construct Port Service Efficiency (0.936; 0.937), Port Digital Transformation/Smart Port (0.937; 0.938), and Port Service Transparency (0.939; 0.940) all exceed the minimum threshold of 0.70 [16].

The Composite Reliability values are 0.946, 0.946, and 0.948, respectively, indicating excellent measurement consistency [18]. In addition, the Average Variance Extracted (AVE) values of 0.635;

0.638; and 0.647 are above the threshold of 0.50, proving the fulfillment of convergent validity, namely the ability of indicators to explain construct variance well [19].

Overall, these results prove that the research instruments have high reliability and validity, so that the results of causal relationship analysis using SEM-PLS can be interpreted with a strong level of scientific confidence and in accordance with reputable empirical research standards.

Model Accuracy Test

The results of the model accuracy test with R Square show that the research model has very strong explanatory power and meets the eligibility criteria in Partial Least Squares Structural Equation Modeling (PLS-SEM) analysis.

Table 10. R Square Test

Variable	R Square	Adjusted R Square
Port Service Efficiency	0.881	0.880
Port Service Transparency	0.907	0.906

Source: Processed Data Results with SEM-PLS, 2025

The R^2 value for the Port Service Efficiency variable is 0.881 (adjusted 0.880), indicating that 88.1% of the variation in service efficiency can be explained by the Port Digital Transformation variable. Meanwhile, the R^2 value for the Port Service Transparency variable is 0.907 (adjusted 0.906), which means that 90.7% of the variation in transparency is also significantly influenced by the level of digital transformation implementation.

Based on PLS-SEM criteria, an R^2 value above 0.67 is categorized as strong, so these two results confirm that the model has a very high predictive ability for the dependent variable[16] . Thus, it can be concluded that port digital transformation plays a major role in determining the improvement of port service efficiency and transparency.

Hypothesis Test Results

The hypothesis testing results in this study provide strong empirical evidence regarding the strategic role of port digital transformation (smart port) in improving port service efficiency and transparency.

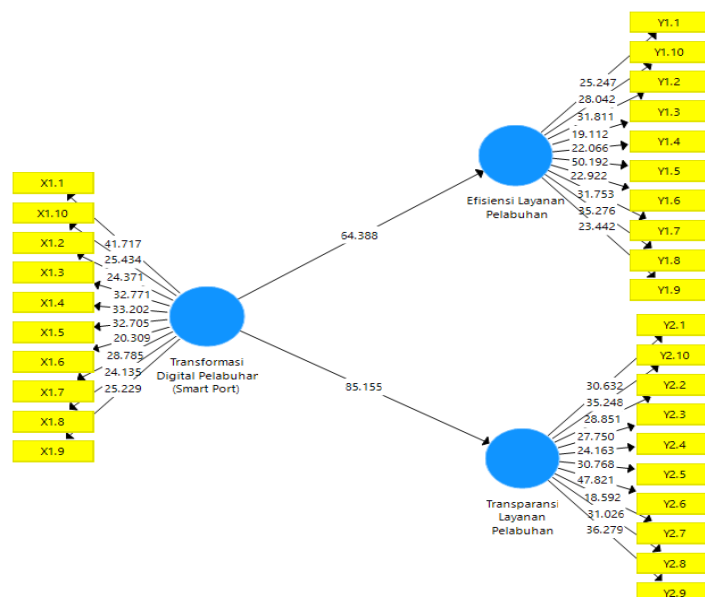


Figure 2. Bootstrapping Results of the Research Model with SEM-PLS Source: Processed Data Results with SEM-PLS, 2025

Table 11. Hypothesis Test Results

Variable Relationships	Original Sample (O)	Sample Mean (M)	Standard Deviation (STDEV)	T Statistics (O/STDEV)	P Values
Digital Port Transformation (Smart Port) → Port Service Efficiency	0.938	0.939	0.014	65.61	0
Digital Transformation of Ports (Smart Port) → Transparency of Port Services	0.952	0.953	0.011	88.165	0

Source: Processed Data Results with SEM-PLS, 2025

The results of testing the model with Structural Equation Modeling–Partial Least Squares (SEM-PLS) show that all relationships between variables are statistically significant and have a positive effect. The path between Port Digital Transformation and Port Service Efficiency produces a coefficient of 0.938, a T-statistic of 65.612, and a p-value of 0.000. Meanwhile, the path between Port Digital Transformation and Port Service Transparency obtained a coefficient of 0.952, a T-statistic of 88.165, and a p-value of 0.000.

All test values exceeded the significance threshold ($p < 0.05$ and $T > 1.96$) as suggested by Hair et al., which means that the research hypothesis was fully accepted. Thus, it can be concluded that the implementation of port digital transformation has a positive and significant effect on the efficiency and transparency of port services [16].

These findings reinforce the theory of digital transformation, which emphasizes the importance of adopting information technology in creating new operational value through efficiency, data integration, and openness of [12], [20]. The results of this study are also in line with the findings of [10] and [21] in the context of European and Asian ports, but with a higher coefficient of influence, indicating that the implementation of smart ports in Indonesia has had a remarkably significant impact on service performance.

Discussion

Digital transformation of ports has been proven to have a very strong and significant positive impact on two key aspects of service performance. The results of the SEM-PLS analysis show that digital transformation affects service efficiency with a coefficient of $\beta = 0.938$ ($T = 65.612$; $p < 0.001$) and service transparency with $\beta = 0.952$ ($T = 88.165$; $p < 0.001$). The determination values of R^2 of 0.881 for efficiency and 0.907 for transparency indicate that more than 88% of the variation in efficiency and more than 90% of the variation in transparency are explained by the implementation of digital transformation. These findings confirm the success of smart port implementation in improving the speed, accuracy, cost efficiency, and transparency of port services.

These results are in line with the concept of digital transformation, which emphasizes the integration of information technology, process automation, and the use of real-time data as the main drivers of efficiency and accountability in public services [12]. Li's research also confirms that digitization can increase throughput and reduce emissions in the port sector, although it does not yet place transparency as a key variable. This study complements it by showing that transparency can be measured empirically and has been proven to increase in line with the level of digital transformation [20].

A comparison with research in Europe reveals an important difference: European ports face coordination barriers among stakeholders, resulting in slow progress in improving transparency [10]. In contrast, ports in Indonesia that have implemented system integration and digital platform innovations show higher levels of transparency, as reflected in stronger R^2 values and path coefficients. Barriers reported in other contexts, such as human resource limitations and interoperability, did not appear dominant in this study due to more effective technology integration and digital resource management [21].

In addition, this study expands on previous national findings [22] that highlight the reduction in logistics costs due to digitalization, adding evidence that transparency is also a significant direct impact of smart port implementation. Thus, this study contributes to Indonesian literature by simultaneously testing efficiency and transparency as twin outcomes of digital transformation.

In practical terms, the resulting policy implications emphasize the importance of strengthening digital system integration, improving platform interoperability, and innovating real-time services. The development of digital human resource capacity and the affirmation of information disclosure regulations are key to the sustainability of smart port implementation in Indonesia. Although based on perceptual data, this study remains methodologically valid. However, further studies are recommended to combine operational data such as loading and unloading times and costs per container to strengthen external validity and test the role of mediating or moderating variables such as port size and organizational culture.

Overall, the results of this study confirm that digital transformation is a key determinant of modern port performance, with an important theoretical contribution that places efficiency and transparency as two equal outcomes of the digitization process, while expanding the global understanding of how smart ports build competitiveness, accountability, and sustainability in Indonesia's maritime sector.

CONCLUSION

This study confirms that port digital transformation is a key determinant of improved port service performance. The developed smart port model has been proven to have a very strong and significant positive influence on operational efficiency and service transparency, with the ability to explain the variation of each variable by more than eighty-eight percent. These findings present a new empirical model of Smart Port Optimization that integrates the use of information technology, automation, system interconnection, and digital platform innovation into a single tested causal framework. This model expands the theoretical understanding of the relationship between digitalization and public service performance in the maritime sector, while providing a practical basis for port managers to design targeted policies and technology investments. The implementation of the resulting model has the potential to accelerate the adoption of smart ports in Indonesia, increase national logistics competitiveness, and become a reference for smart port development in other maritime regions with similar characteristics.

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