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MEASURING PORT DIGITALISATION AND ITS OUTCOMES AT THE PORT COMMUNITY LEVEL: DEVELOPMENT AND VALIDATION OF A MULTIDIMENSIONAL INSTRUMENT, EVIDENCE FROM THE MOROCCAN PORT SYSTEM

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Abstract:
Research on port digitalisation increasingly relies on surveys of port actors, yet few studies report how their measures were developed and validated, and no instrument jointly captures port digital maturity, its organisational enablers and the four dimensions of port performance. This article develops and validates such an instrument. Thirty-seven items measuring eight constructs — digital maturity, digital dynamic capabilities, port community governance, digital skills, and operational, economic, environmental and social performance — were derived from published scales and port indices, reviewed by experts, back-translated between French and Arabic, and pre-tested. The instrument was administered to 150 members of the port communities of Tanger Med and of the ports managed by Morocco's National Ports Agency in 2026. Exploratory factor analysis recovered the eight intended factors without cross-loadings above 0.30, although parallel analysis suggested a more parsimonious solution. After removing two items, a confirmatory factor analysis of the 35-item model showed good fit (χ^2/df = 1.10; CFI = 0.977; TLI = 0.974; RMSEA = 0.026; SRMR = 0.053). Composite reliabilities ranged from 0.79 to 0.88, all average variances extracted exceeded 0.50, and discriminant validity was supported by the Fornell–Larcker criterion and heterotrait–monotrait ratios below 0.60. Compositional invariance held across the two port units, known-groups comparisons distinguished Tanger Med from the other ports on digital maturity (d = 0.68), and correlations followed theoretical expectations. The instrument offers researchers and port managers a validated tool for assessing digitalisation and its outcomes; its main limitation is the weaker measurement of social performance.

Keywords: port digitalisation; scale development; port performance measurement; digital maturity; confirmatory factor analysis

1. Introduction

Measuring port performance has long been a central concern of port economics. The notion has expanded from the physical productivity of berths measured by early UNCTAD indicators to economic efficiency (Talley, 1994, 2006), integration into supply chains (Bichou & Gray, 2004; Robinson, 2002), service effectiveness as perceived by users (Brooks & Schellinck, 2013) and sustainability (Lim et al., 2019). In parallel, the digitalisation of ports has generated a stream of indices designed to assess how far ports have adopted smart-port technologies (González et al., 2020; Molavi et al., 2020; Philipp, 2020; Triska et al., 2024). As research turns from describing digitalisation to explaining its consequences, a growing number of studies rely on surveys of port actors analysed with structural equation models (Caldeirinha et al., 2020; Jiang et al., 2023; Kishore et al., 2025; Sirajuddin et al., 2026; Zhao et al., 2026).

The main research problem lies in the quality of the measures underlying this survey-based evidence. Smart-port indices were designed to rank ports, not to measure latent constructs at the level of the organisations that make up a port community, and they have not been subjected to psychometric validation (Molavi et al., 2020; Philipp, 2020). Validated scales of dynamic capabilities (Kump et al., 2019; Wilden et al., 2013) and of digital skills (van Deursen et al., 2016) were developed outside the port sector. Performance measures, finally, tend to cover one or two dimensions, whereas the literature conceives port performance as multidimensional (Lim et al., 2019; O'Connor et al., 2019). Moreover, the performance of a port is a collective outcome produced by a community of legally independent organisations (Heilig et al., 2017), which raises the question of whether individual members can reliably assess it. Without validated measures, the dispersion of findings on the digitalisation–performance relationship, which ranges from positive effects (Li et al., 2025) to negative associations (Yen et al., 2023), cannot be disentangled from measurement artefacts.

This article therefore addresses the following research question: **can digital maturity, its organisational enablers and the four dimensions of port performance be measured reliably and validly at the level of port community members?** Two sub-questions follow: (a) Does the factor structure of an instrument derived from the literature correspond to the intended constructs? (b) Does the instrument meet established criteria of reliability, convergent and discriminant validity, invariance across port units and known-groups validity?

The article makes three contributions. First, it proposes a 35-item instrument that jointly measures port digital maturity, digital dynamic capabilities, port community governance, digital skills and operational, economic, environmental and social performance, with every item traced to its source in the literature. Second, it validates the instrument with a combination of exploratory and confirmatory factor analyses and composite-based criteria, following the recommended two-step logic (Anderson & Gerbing, 1988) and established construct-validation procedures (MacKenzie et al., 2011). Third, it does so in an emerging African port system whose two port units differ markedly in digital maturity, which allows invariance and known-groups validity to be tested.

The article is structured as follows. Section 2 reviews the measurement literature underlying the eight constructs. Section 3 presents the development procedure and the validation methods. Section 4 reports the results. Section 5 discusses the contributions, uses and limitations of the instrument, and Section 6 concludes. Supplementary File S1 provides the full wording of the questionnaire in English and French.

2. Measurement literature

2.1. Port digital maturity

Port digitalisation can be described in layers: an informational layer of paperless procedures and electronic data exchange, an operational layer of automation and real-time tracking, and an analytical layer of data analytics and artificial intelligence (Heilig & Voß, 2017). Several indices operationalise these layers. Philipp (2020) proposes a digital readiness index of 38 indicators applied to five European ports. Molavi et al. (2020) propose a smart port index based on key performance indicators in operations, environment, energy, safety and security. González et al. (2020) build a smart port indicator to rank Spanish ports, and Triska et al. (2024) propose a maturity model for smart port terminals in six domains, tested on two Brazilian terminals. Caldeirinha et al. (2020) identify characteristics of port community systems related to performance. These sources converge on six practices — paperless procedures, automatic data exchange, automation of physical operations, real-time tracking, analytics and artificial intelligence, and electronic payment — but none was designed as a reflective scale for survey respondents.

2.2. Digital dynamic capabilities, governance and digital skills

Dynamic capabilities refer to the ability to integrate, build and reconfigure competences in changing environments (Teece et al., 1997) and comprise sensing, seizing and reconfiguring (Teece, 2007). Kump et al. (2019) developed and validated a scale measuring these three capacities, and Wilden et al. (2013) measured dynamic capabilities in relation to performance; Warner and Wäger (2019) describe the specific capabilities required by digital transformation. In ports, Kishore et al. (2025) relate dynamic capabilities to port performance, while Mara and Mokoena (2024) note the scarcity of research on the digital dynamic capabilities of ports.

The governance of a port community concerns information sharing, coordination by the port authority, data-governance rules and trust. Paulraj et al. (2008) validated measures of inter-organisational communication in supply relationships, Jiang et al. (2023) examined port-centric information integration in Qingdao, and Sirajuddin et al. (2026) modelled integrated port governance and digitalisation in Indonesia. Digital skills, finally, were measured by van Deursen et al. (2016), whose Internet Skills Scale distinguishes operational, information-navigation and other skills, while Gekara and Nguyen (2018) document how computerisation and automation transform skill requirements in container terminals.

2.3. Multidimensional port performance

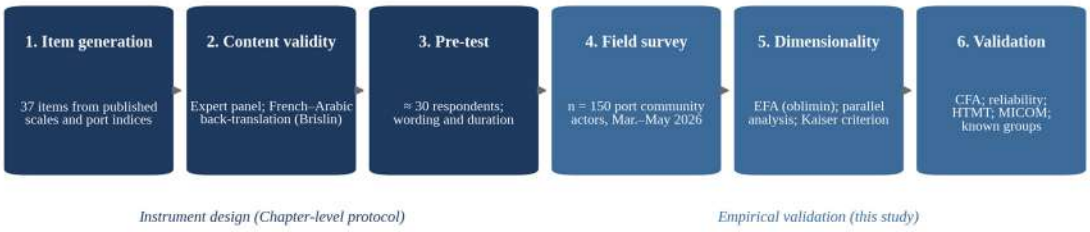
Port performance indicators were first defined by UNCTAD in operational terms and later linked to strategic objectives (UNCTAD, 2016). Talley (1994, 2006) frames port performance from an economic perspective, and Bichou and Gray (2004) argue for a logistics and supply-chain approach. Woo et al. (2011) relate port evolution to performance in changing logistics environments, Ha et al. (2019) propose a multi-stakeholder perspective on port performance in container logistics, and Brooks and Schellinck (2013) examine what determines users' evaluations of port service delivery. The environmental and social dimensions have been operationalised by Lu et al. (2016), who examine sustainability performance from port managers' perspectives, by Puig et al. (2014), who identify environmental performance indicators for ports, and by Lim et al. (2019), whose systematic review organises port sustainability performance into economic, environmental and social dimensions. O'Connor et al. (2019) note that measurement techniques have progressed considerably while port performance itself remains weakly conceptualised.

3. Methodology

3.1. Development procedure

The instrument was developed following established guidelines for survey-measure development (Hinkin, 1998; MacKenzie et al., 2011) in six stages (Figure 1).

Figure 1. Development and validation procedure of the instrument.



Item generation. Each construct was defined from the literature, and items were adapted from published scales or from dimensions identified in peer-reviewed port studies (Table 1). Digital maturity was measured by six items covering the layers of the smart-port architecture. Digital dynamic capabilities were measured by six items covering sensing, seizing and reconfiguring. Governance and digital skills were measured by four items each. The four performance dimensions were measured by items capturing the change observed over the previous three years: five operational, four economic, four environmental and four social items. All items used a five-point Likert scale (1 = strongly disagree; 5 = strongly agree). The full wording of all items, in English and French, together with the instructions and response scale, is reported in Supplementary File S1.

Content validity, translation and pre-test. A panel of academic and professional experts assessed the relevance and clarity of the items. The instrument was translated and back-translated between French and Arabic (Brislin, 1970) and pre-tested with about thirty respondents to check comprehension and completion time. Procedural remedies against common method bias were applied: anonymity, separation of the predictor and criterion blocks, and neutral wording (Podsakoff et al., 2003).

3.2. Field survey

The population comprises the organisations belonging to the port communities of Tanger Med and of the ports managed by Morocco's National Ports Agency (ANP). Tanger Med operates its own port community system, which made paperless port

passage mandatory in February 2022 (Tanger Med Port Community System, 2022), while ANP ports rely on the national single window PortNet. Purposive sampling with quotas by port and actor category was used, as in comparable studies (Kishore et al., 2025; Sirajuddin et al., 2026). Between 2 March and 10 May 2026, 150 usable responses were collected: 56 from Tanger Med and 94 from ANP ports; 26.0% from freight forwarders, 16.0% from terminal operators, 16.0% from shippers, 12.7% from shipping agents and carriers, 9.3% from road hauliers, 8.0% from port authorities, 6.7% from public administrations and 5.3% from other actors. Respondents had a mean seniority of 13.3 years (SD = 6.2) in the port sector. There were no missing values on construct items and no straight-lined responses.

3.3. Validation methods

Item analysis. Item means, standard deviations, skewness, kurtosis and corrected item–total correlations were examined.

Dimensionality. Sampling adequacy was assessed with the Kaiser–Meyer–Olkin (KMO) index (Kaiser, 1974) and Bartlett's test. The number of factors was examined with the Kaiser criterion (Kaiser, 1960) and with Horn's (1965) parallel analysis based on 500 random data sets (95th percentile). An exploratory factor analysis (EFA) with minimum residual extraction and oblique (oblimin) rotation was then estimated with eight factors. Because these criteria can diverge, the number of factors was decided by weighing them against the a priori structure of the instrument and the interpretability of the competing solutions, rather than by applying a single rule mechanically (Fabrigar et al., 1999).

Confirmatory factor analysis. A correlated eight-factor confirmatory factor analysis (CFA) was estimated by maximum likelihood (Wishart) with the semopy package in Python, first on the 37 items and then on the retained items. Fit was assessed with χ^2/df, the comparative fit index (CFI), the Tucker–Lewis index (TLI), the root mean square error of approximation (RMSEA) with its 90% confidence interval and the standardised root mean square residual (SRMR), using the cut-offs of Hu and Bentler (1999). Composite reliability and average variance extracted (AVE) were computed from standardised loadings (Fornell & Larcker, 1981).

Composite-based assessment. Because the instrument is intended for partial least squares structural equation modelling (PLS-SEM), the measurement model was also assessed with composite-based criteria (Hair et al., 2019): indicator loadings (≥ 0.708), Cronbach's alpha, ρA and ρC (0.70–0.95), AVE (≥ 0.50) and the heterotrait–monotrait ratio (HTMT < 0.85; Henseler et al., 2015). Items were removed if their loading lay between 0.40 and 0.708 and their removal increased composite reliability or AVE (Hair et al., 2019). As digital maturity aggregates practices that are not interchangeable, a formative (Mode B) specification was also estimated (Hair et al., 2022; Jarvis et al., 2003).

Common method variance. Harman's single-factor test and the full collinearity test (VIF < 3.3; Kock, 2015) were applied, bearing in mind that both are only diagnostic (Podsakoff et al., 2012).

Invariance and known-groups validity. Measurement invariance across Tanger Med and ANP ports was tested with the measurement invariance of composite models (MICOM) procedure (Henseler et al., 2016): configural invariance (step 1), compositional invariance (step 2) and equality of composite means and variances (step 3) using 5,000 permutations. Known-groups validity was assessed by comparing the two units with Welch's t-tests and Cohen's d, the expectation being that Tanger Med respondents report higher digital maturity, as documented by public sources (Tanger Med Port Community System, 2022; World Bank & S&P Global Market Intelligence, 2025).

Nomological validity and sensitivity. Correlations between constructs were examined against theoretical expectations. Because some respondents may not observe certain performance outcomes (for instance, emissions), reliability was re-estimated on the subsample of respondents most directly involved in port operations (port authorities, terminal operators, shipping agents and carriers, administrations and other actors; n = 73).

4. Results

4.1. Item analysis and dimensionality

Item means ranged from 3.31 to 3.87 and standard deviations from 0.90 to 1.13; skewness ranged from −0.63 to 0.00 and kurtosis from −0.88 to −0.02, within usual limits for normality (Kline, 2016). Corrected item–total correlations ranged from 0.47 (DM5) to 0.76. Sampling adequacy was good (KMO = 0.843), and Bartlett's test was significant (χ^2 = 2,853.6; df = 666; p < .001).

Eight eigenvalues exceeded one (8.999 to 1.346; the ninth was 0.958), consistent with the eight intended constructs, whereas parallel analysis retained six factors. Given this divergence between criteria, and because the eight constructs had been defined a priori from the literature, the eight-factor solution was estimated and judged on its interpretability; the parallel-analysis result is nonetheless reported as a reason to confirm the structure on an independent sample. As shown in Table 1, every item loaded on its intended factor, with primary loadings between 0.54 and 0.85 for the retained items and no cross-loading above 0.23. The eight factors explained 51.8% of the variance. Two items displayed weaker primary loadings: DM5 (analytics and artificial intelligence; 0.38) and SO2 (occupational health and safety; 0.57).

Three considerations justify retaining the eight-factor structure despite the parallel-analysis result. First, the structure is grounded in theory. Each construct was defined a priori and draws on a distinct body of work: smart-port indices for digital maturity (Philipp, 2020; Triska et al., 2024), the dynamic-capability view for digital dynamic capabilities (Kump et al., 2019; Teece, 2007), research on inter-organisational communication for governance (Paulraj et al., 2008), digital-skills research for skills (van Deursen et al., 2016) and the multidimensional conception of port performance (Lim et al., 2019). Methodological guidance recommends that factor retention combine statistical criteria with theoretical meaning and interpretability (Fabrigar et al., 1999), even though parallel analysis is among the most accurate of the statistical criteria (Hayton et al., 2004). Second, the version of parallel analysis applied here is conservative. It compares every observed eigenvalue with the 95th percentile of random eigenvalues, whereas simulation evidence shows that this criterion is best suited to the first eigenvalue and that a less stringent criterion performs better for later eigenvalues when factors are more than minimally correlated (Crawford et al., 2010), as they are among the digitalisation constructs and among the performance dimensions in this study. Retaining too few factors is also generally viewed as a more serious error than retaining too many, because it forces conceptually distinct constructs into the same factor (Fabrigar et al., 1999). Third, the eight-factor solution is empirically coherent. Each factor was defined by four to six items, no item cross-loaded meaningfully, and the confirmatory and discriminant-validity results (Sections 4.3 and 4.4) show that even the two most closely related pairs of constructs remain distinct (HTMT = 0.591 and 0.569). A six-factor solution would therefore have merged constructs that the data otherwise separate. The structure nonetheless needs to be confirmed on an independent and larger sample, as discussed in Section 5.3.

Table 1. Items, sources and item-level results (n = 150)

Code	Item (abridged)	Source(s)	M	SD	CITC	EFA λ	CFA λ
DM1	Port documentary procedures are fully paperless	Philipp (2020); Caldeirinha et al. (2020)	3.57	1.02	0.72	0.72	0.78
DM2	Our systems exchange data automatically with other actors (PCS, single window)	Molavi et al. (2020); Caldeirinha et al. (2020)	3.47	0.97	0.72	0.73	0.79
DM3	Physical operations (gates, yard, handling) are automated or remotely controlled	Triska et al. (2024); Molavi et al. (2020)	3.55	1.08	0.69	0.72	0.76
DM4	We track vessels, cargo or equipment in real time	Philipp (2020); Triska et al. (2024)	3.52	1.05	0.70	0.70	0.73
DM5[a]	We use data analytics or AI to plan or forecast operations	Triska et al. (2024); Caldeirinha et al. (2020)	3.55	1.01	0.47	0.38	—
DM6	Port-related payments and invoicing are electronic	Philipp (2020)	3.49	1.05	0.64	0.54	0.74
DC1	We quickly identify technological changes affecting our activity	Kump et al. (2019); Warner and Wäger (2019)	3.60	1.09	0.70	0.74	0.75
DC2	We systematically observe the digital practices of other ports and logistics actors	Kump et al. (2019); Wilden et al. (2013)	3.66	0.98	0.61	0.68	0.64
DC3	We decide quickly to invest in promising digital solutions	Kump et al. (2019); Warner and Wäger (2019)	3.62	1.03	0.73	0.78	0.79
DC4	We mobilise the resources needed to implement new digital tools	Wilden et al. (2013)	3.51	1.07	0.74	0.70	0.82
DC5	We adapt our processes to take advantage of digital tools	Kump et al. (2019); Warner and Wäger (2019)	3.65	1.00	0.70	0.71	0.75
DC6	We reallocate resources and skills when new technologies require it	Wilden et al. (2013)	3.59	1.06	0.66	0.66	0.72
GOV1	Community actors share useful information in a timely and reliable way	Paulraj et al. (2008); Jiang et al. (2023)	3.36	1.02	0.64	0.66	0.73
GOV2	The port authority effectively coordinates actors around common digital projects	Sirajuddin et al. (2026)	3.31	0.98	0.67	0.72	0.76
GOV3	Rules on access, ownership and use of shared data are clearly defined	Sirajuddin et al. (2026); Paulraj et al. (2008)	3.37	1.04	0.62	0.66	0.70
GOV4	Actors trust each other to exchange data	Paulraj et al. (2008)	3.39	0.98	0.68	0.83	0.77
SK1	Staff master the digital tools used in their port tasks	van Deursen et al. (2016)	3.53	1.13	0.72	0.77	0.79
SK2	Staff can search, interpret and use the data produced by these tools	van Deursen et al. (2016)	3.51	1.04	0.72	0.78	0.79
SK3	Staff adapt quickly to new systems	Gekara and Nguyen (2018)	3.60	1.08	0.71	0.72	0.80

Code	Item (abridged)	Source(s)	M	SD	CITC	EFA λ	CFA λ
SK4	We regularly train staff in new digital tools	Gekara and Nguyen (2018)	3.55	1.05	0.66	0.69	0.72
OP1	Vessel waiting and port stay times have decreased	Woo et al. (2011); UNCTAD (2016)	3.83	0.90	0.71	0.76	0.77
OP2	Cargo-handling productivity has improved	Ha et al. (2019); UNCTAD (2016)	3.85	0.95	0.71	0.71	0.79
OP3	Cargo dwell time in the port has decreased	Ha et al. (2019)	3.87	0.97	0.70	0.65	0.79
OP4	Truck gate passage time has decreased	Ha et al. (2019)	3.73	0.95	0.65	0.67	0.70
OP5	Reliability and predictability of operations have improved	Woo et al. (2011)	3.79	0.97	0.62	0.62	0.67
EC1	Port passage costs borne by us or our clients have decreased	Woo et al. (2011); Ha et al. (2019)	3.61	0.94	0.57	0.59	0.62
EC2	The profitability of our port activities has improved	Kishore et al. (2025)	3.69	0.99	0.67	0.73	0.75
EC3	The port attracts more traffic and shipping services	Ha et al. (2019)	3.47	0.93	0.66	0.67	0.76
EC4	The port's competitiveness relative to competitors has strengthened	Kishore et al. (2025); Woo et al. (2011)	3.57	0.98	0.68	0.69	0.79
EN1	Energy consumption of port operations has decreased	Lu et al. (2016); Puig et al. (2014)	3.45	1.05	0.66	0.77	0.74
EN2	Greenhouse gas and pollutant emissions have decreased	Lu et al. (2016); Lim et al. (2019)	3.39	1.07	0.76	0.85	0.86
EN3	Management of waste, water and noise has improved	Puig et al. (2014)	3.32	1.11	0.60	0.56	0.70
EN4	Compliance with environmental requirements has strengthened	Lu et al. (2016)	3.31	1.04	0.57	0.54	0.66
SO1	Employees' skills and training have developed	Lim et al. (2019)	3.46	1.03	0.63	0.72	0.77
SO2 [a]	Occupational health and safety have improved	Lim et al. (2019); Lu et al. (2016)	3.41	1.02	0.49	0.57	—
SO3	Satisfaction of users and stakeholders has increased	Brooks and Schellinck (2013)	3.38	1.01	0.63	0.76	0.81
SO4	The quality of port-related jobs has improved	Lim et al. (2019)	3.40	1.00	0.64	0.73	0.65

Note. DM = digital maturity; DC = digital dynamic capabilities; GOV = port community governance; SK = digital skills; OP, EC, EN, SO = operational, economic, environmental and social performance (change over the previous three years). CITC = corrected item–total correlation; EFA λ = primary oblimin loading (eight-factor solution, 37 items); CFA λ = standardised loading in the final 35-item model. [a] Item removed. Full item wording in English and French is given in Supplementary File S1.

4.2. Item reduction

In the composite-based assessment of the initial 37-item model, DM5 (0.600) and SO2 (0.497) were the only items loading below 0.708 on their construct. Their removal increased the AVE of digital maturity from 0.596 to 0.658 and that of social

performance from 0.584 to 0.697, and they were therefore removed (Hair et al., 2019). The decision converges with the item analysis: DM5 and SO2 had the lowest corrected item–total correlations (0.47 and 0.49), the weakest EFA loadings within their factors and the lowest CFA loadings in the initial model (0.52 and 0.53). Two substantive interpretations are plausible: the use of analytics and artificial intelligence may not yet be diffused enough among Moroccan port actors to be part of the same continuum as more established practices, and occupational safety may follow a logic distinct from the other social outcomes. Both interpretations remain to be tested.

4.3. Confirmatory factor analysis

The initial 37-item CFA fitted the data acceptably (χ^2 = 710.3; df = 601; χ^2/df = 1.18; CFI = 0.956; TLI = 0.951; RMSEA = 0.035, 90% CI [0.023, 0.045]; SRMR = 0.057). The final 35-item model fitted better (χ^2 = 587.1; df = 532; χ^2/df = 1.10; CFI = 0.977; TLI = 0.974; RMSEA = 0.026, 90% CI [0.002, 0.039]; SRMR = 0.053), meeting all cut-offs proposed by Hu and Bentler (1999). All standardised loadings were significant ($p < .001$) and ranged from 0.62 (EC1) to 0.86 (EN2). Table 2 reports reliability and convergent validity under both the covariance-based and composite-based approaches.

Table 2. Reliability and convergent validity of the final measurement model (n = 150)

Construct	Items	CFA λ range	CFA CR	CFA AVE	PLS λ range	α	ρA	ρC	PLS AVE
Digital maturity	5	0.73–0.79	0.870	0.573	0.791–0.827	0.869	0.871	0.906	0.658
Digital dynamic capabilities	6	0.64–0.82	0.882	0.556	0.696–0.844	0.882	0.895	0.910	0.628
Governance	4	0.70–0.77	0.828	0.547	0.785–0.837	0.827	0.836	0.885	0.658
Digital skills	4	0.72–0.80	0.858	0.602	0.796–0.857	0.857	0.867	0.903	0.700
Operational performance	5	0.67–0.79	0.862	0.556	0.733–0.840	0.861	0.869	0.900	0.643
Economic performance	4	0.62–0.79	0.822	0.538	0.712–0.850	0.821	0.839	0.881	0.650
Environmental performance	4	0.66–0.86	0.830	0.553	0.767–0.875	0.822	0.824	0.883	0.654
Social performance	3	0.65–0.81	0.792	0.561	0.745–0.908	0.790	0.889	0.873	0.697

Note. CR = composite reliability; AVE = average variance extracted. CFA estimates from the covariance-based model (maximum likelihood); PLS estimates from the composite-based model (Mode A).

Reliability was satisfactory for all constructs, with composite reliabilities between 0.79 and 0.88 in the CFA and between 0.873 and 0.910 in PLS, and Cronbach's alphas

between 0.790 and 0.882. All AVEs exceeded 0.50 under both approaches. One anomaly concerns social performance: its ρA (0.889) exceeds ρC (0.873), whereas ρA normally lies between alpha and ρC (Dijkstra & Henseler, 2015). This pattern indicates very unequal indicator weights among the three remaining items and suggests that the construct is measured less consistently than the others.

4.4. Discriminant validity

The highest correlation between latent factors in the CFA was 0.582 (economic and operational performance), whose square (0.339) is below the lowest AVE (0.538); the Fornell–Larcker criterion was therefore met (Fornell & Larcker, 1981). In the composite-based model, the square root of each AVE exceeded the construct's correlations with all other constructs, every item loaded more highly on its own construct than on any other, and the HTMT ratios ranged from 0.038 to 0.591, well below 0.85 (Henseler et al., 2015). Table 3 reports the HTMT matrix.

Table 3. Heterotrait–monotrait ratios (n = 150)

	DM	DC	GOV	SK	OP	EC	EN
DC	0.569						
GOV	0.255	0.183					
SK	0.394	0.556	0.072				
OP	0.458	0.214	0.442	0.120			
EC	0.404	0.133	0.331	0.038	0.591		
EN	0.507	0.302	0.350	0.222	0.503	0.562	
SO	0.224	0.166	0.044	0.258	0.267	0.162	0.194

4.5. Common method variance

Harman's first factor explained 25.1% of the variance of the retained items, and the full collinearity VIFs ranged from 1.11 to 1.70, below 3.3 (Kock, 2015). Combined with the clean discriminant pattern — several conceptually distant constructs, such as governance and social performance, correlate close to zero (r = 0.03 in the CFA) — these diagnostics suggest that a general method factor does not dominate the responses, although they cannot rule it out (Podsakoff et al., 2012).

4.6. Formative specification of digital maturity

Re-estimating digital maturity as a formative composite including all six items yielded indicator VIFs between 1.38 and 2.11, well below the threshold of collinearity concern (Hair et al., 2022). Only the weight of DM6 (electronic payment; 0.459; 95% CI [0.190,

0.674]) was significant, but all indicator loadings were significant and ranged from 0.603 (DM5) to 0.856 (DM6); following Hair et al. (2019), indicators with non-significant weights but substantial loadings were retained. The formative composite's associations with operational (0.368), economic (0.379) and environmental (0.427) performance were close to those obtained with the reflective specification (0.344, 0.419 and 0.413), indicating that substantive conclusions do not depend on the measurement model chosen for digital maturity.

4.7. Invariance across port units and known-groups validity

The MICOM procedure established configural invariance, since the same items, data treatment and algorithm settings were used for both groups, and compositional invariance, with a minimum compositional correlation of 0.977, which fell within the permutation distribution for every construct (Henseler et al., 2016). In step 3, composite variances did not differ between the units for any construct, whereas composite means differed for digital maturity, digital dynamic capabilities, governance, operational and environmental performance. Partial measurement invariance is thus established: the instrument measures the constructs in the same way in both units, which allows path coefficients to be compared across them, while the mean differences reflect genuine differences between the units rather than measurement artefacts. This conclusion follows directly from the logic of MICOM. The procedure establishes partial invariance when configural (step 1) and compositional (step 2) invariance hold, and full invariance only when, in addition, composite means and variances are equal across groups (step 3; Henseler et al., 2016). Here, steps 1 and 2 were satisfied for every construct, and step 3 showed equal variances but different means for five constructs, so full invariance could not be claimed for them. Partial invariance is the appropriate conclusion: it is sufficient to compare path coefficients between Tanger Med and ANP ports, but not to pool the two groups without accounting for group membership (Henseler et al., 2016). For digital skills, economic performance and social performance, whose means and variances did not differ, full invariance holds.

These mean differences provide evidence of known-groups validity (Table 4). As expected from public evidence on Tanger Med's digital lead — its community system made paperless passage mandatory in 2022 (Tanger Med Port Community System, 2022) and the port ranks among the world's top container ports for vessel time in port

(World Bank & S&P Global Market Intelligence, 2025) — Tanger Med respondents reported markedly higher digital maturity (d = 0.68), as well as higher dynamic capabilities, governance quality, and operational and environmental performance. Differences in digital skills, economic and social performance were not significant.

Table 4. Known-groups comparison: Tanger Med (n = 56) versus ANP ports (n = 94)

Construct	Mean difference (SD units)	Welch t	p	Cohen's d
Digital maturity	0.646	4.07	< .001	0.68
Digital dynamic capabilities	0.461	2.76	.007	0.47
Governance	0.483	2.83	.006	0.49
Digital skills	0.164	0.93	.353	0.16
Operational performance	0.489	2.92	.004	0.50
Economic performance	0.310	1.89	.062	0.31
Environmental performance	0.406	2.43	.017	0.41
Social performance	0.219	1.35	.181	0.22

Note. Differences computed on standardised composite scores.

4.8. Nomological validity and sensitivity

The correlation pattern is consistent with theory. Digital maturity correlated positively with all performance dimensions, most strongly with environmental (0.48), operational (0.45) and economic performance (0.40), and only weakly with social performance (0.23) (CFA estimates). Digital dynamic capabilities correlated most strongly with digital maturity (0.58) and digital skills (0.57), in line with the view that capabilities build on technological and human resources (Teece, 2007; Warner & Wäger, 2019). Governance correlated with operational performance (0.45) but not with digital skills (0.08), which supports their distinctiveness as organisational and human enablers.

In the subsample of respondents most directly involved in port operations (n = 73), Cronbach's alphas remained between 0.812 and 0.868 for all constructs except social performance (0.715), indicating that reliability does not depend on the inclusion of actors more distant from port operations, but confirming the comparatively weaker measurement of social performance.

5. Discussion

5.1. Contributions

The instrument addresses a gap between smart-port indices designed to rank ports (González et al., 2020; Molavi et al., 2020; Philipp, 2020) and survey-based studies that rarely document the development of their measures. By tracing each item to its source

and combining exploratory, confirmatory and composite-based evidence, the article responds to calls for rigorous construct validation (MacKenzie et al., 2011) and offers a measure of port digital maturity that is reliable, distinct from its organisational enablers and invariant across port units with very different digital profiles.

The results also show that members of a port community — including forwarders, shippers and hauliers — can assess collective port outcomes with acceptable reliability, since the reliability of the performance constructs did not deteriorate when the analysis was restricted to the actors most involved in port operations. This supports the use of community-level surveys alongside objective indicators, which remain scarce for many ports (UNCTAD, 2016).

5.2. Uses of the instrument

For researchers, the instrument can serve as a common measurement basis for comparative studies of port digitalisation across countries, allowing results to be accumulated rather than produced with ad hoc measures. Its composite-based and covariance-based properties make it usable with both PLS-SEM and covariance-based SEM. For port authorities and single-window operators, the instrument can be used as a diagnostic tool: periodic administration would allow digital maturity, governance and skills to be monitored across port units and actor categories, and gaps — for instance in data-governance rules (GOV3) or training (SK4) — to be identified.

5.3. Refinements needed

Four refinements are warranted. First, the social performance construct showed the weakest measurement properties — three remaining items, unequal weights and lower reliability among operational actors — and should be extended with items covering employment, working conditions and occupational safety as distinct facets (Lim et al., 2019). Second, five items combine two objects (DM3, DM4, OP1, EN3 and SO2) to remain faithful to their sources; future versions should split them. Third, items on analytics and artificial intelligence should be re-examined as these technologies diffuse, possibly as a separate analytical-maturity sub-dimension.

The detachment of SO2 (occupational health and safety) from the other social items can be interpreted in light of the characteristics of port work. First, safety follows a regulatory and technical logic that differs from the developmental logic of the retained

items, which concern skills, user satisfaction and job quality. Port work is still regarded as an occupation with very high accident rates, and safety is governed by dedicated codes of practice and safety management arrangements (International Labour Office [ILO], 2018). Changes in safety may therefore depend on compliance requirements and investment cycles rather than on the broader social outcomes captured by SO1, SO3 and SO4. Second, the effect of technological change on safety is ambivalent. Automation and remote operation can remove workers from hazardous quay and yard areas, yet the long-run study of the port of Genoa by Fabiano et al. (2010) found that the shift to container handling coincided with a rise in injury frequency, which the authors linked to a less experienced workforce and to safety measures that did not keep pace with the new technology. Respondents may therefore perceive changes in safety that diverge from changes in the other social outcomes. Third, safety outcomes are concentrated among dock workers and terminal staff, so many respondents — shippers, forwarders and hauliers in particular — observe them only indirectly, which is likely to add measurement error. Finally, the item combines two objects, health and safety, which may have changed differently. Taken together, these interpretations suggest that occupational health and safety should be measured as a distinct facet rather than as one indicator of a single social construct.

Table 5 proposes candidate items for a revised social performance measure. They build on the social dimension of port sustainability performance described by Lim et al. (2019) and give occupational health and safety its own sub-scale, informed by the ILO (2018) code of practice and by Fabiano et al. (2010). In a future study, these items could be modelled as first-order facets of a higher-order social performance construct, and they should be accompanied by a "don't know / not observed" option so that respondents who do not observe safety outcomes are not forced to guess. Perceived safety improvements should also be compared with objective accident records where port authorities publish them.

Table 5. Candidate items for a revised social performance construct

Facet	Candidate item (stem: "Over the past three years, …")	Grounding
Occupational health and safety	OHS1 — The frequency of occupational accidents in port operations has decreased.	ILO (2018); Fabiano et al. (2010)
	OHS2 — Workers' exposure to hazardous areas (quayside, yard, lashing) has decreased thanks to automation or remote operation.	Fabiano et al. (2010); ILO (2018)
	OHS3 — Occupational health risks for port staff (noise,	ILO (2018)

Facet	Candidate item (stem: "Over the past three years, …")	Grounding
	exhaust fumes, physical strain) have decreased.	
	OHS4 — Safety training and procedures for port staff have been strengthened.	ILO (2018)
Employment	EMP1 — Digitalisation has preserved or created jobs in our organisation.	Gekara and Nguyen (2018); Lim et al. (2019)
	EMP2 — Port-related jobs have become more stable.	Lim et al. (2019)
Working conditions	WC1 — The workload and working hours of port staff have become more manageable.	Lim et al. (2019)
	WC2 — Digital tools have reduced repetitive or physically demanding tasks.	Gekara and Nguyen (2018)
Skills and stakeholders	SO1, SO3, SO4 — Retained items of the present instrument (skills and training; user and stakeholder satisfaction; job quality).	Lim et al. (2019); Brooks and Schellinck (2013)
	COM1 — Relations between the port and surrounding local communities have improved.	Lim et al. (2019)

Note. Proposed items for future testing; they were not administered in the present study. OHS = occupational health and safety; EMP = employment; WC = working conditions; COM = port–community relations. Each item should offer a "don't know / not observed" option.

Fourth, and most importantly, the eight-factor structure retained on theoretical grounds must be confirmed on an independent and larger sample. Parallel analysis suggested six factors, and a sample of 150 is modest for a 35-item, eight-factor model (Kline, 2016). Scale-development guidelines recommend that confirmatory evidence be obtained from a sample different from the one used to derive the factor structure (Hinkin, 1998). A confirmatory study on new data should therefore compare the eight-factor model with the most plausible parsimonious alternatives — in particular, models merging digital maturity with digital dynamic capabilities and operational with economic performance, the two most closely related pairs (Table 3) — using chi-square difference tests and information criteria. It should also extend invariance testing to actor categories and to other national port systems. The eight-factor structure can be regarded as stable only if it outperforms these alternatives on independent data.

6. Conclusion

This article developed and validated a 35-item instrument measuring port digital maturity, digital dynamic capabilities, port community governance, digital skills and operational, economic, environmental and social port performance at the level of port community members. On a sample of 150 actors from the Moroccan port system, exploratory factor analysis recovered the eight intended constructs, the final confirmatory model fitted well (CFI = 0.977; RMSEA = 0.026; SRMR = 0.053),

reliability and convergent validity were satisfactory, and discriminant validity was established by the Fornell–Larcker criterion and HTMT ratios. The instrument showed compositional invariance across Tanger Med and ANP ports, discriminated between them on digital maturity, and behaved as expected within its nomological network.

Three recommendations follow. Researchers should use and report validated multidimensional measures when studying port digitalisation, and should test invariance before comparing port units. Port authorities and single-window operators could administer the instrument periodically to monitor digital maturity and its enablers across actor categories. Policymakers should complement such perception-based monitoring with the publication of objective operational and environmental indicators.

The study has limitations. The sample of 150 respondents is modest for a 35-item CFA, and parallel analysis suggested fewer factors than retained, so the factor structure should be confirmed on an independent and larger sample. Sampling was non-probabilistic, and the instrument was validated in a single country. The performance items rely on perceptions of change over three years and were not validated against objective indicators. The instrument did not include a “don’t know” option or a marker variable, which limits the assessment of common method variance. Test–retest reliability was not assessed. Finally, the article does not report a quantitative agreement index for the expert review; future applications of the instrument should report item- and scale-level content validity indices (Lynn, 1986; Polit & Beck, 2006).

Future research should cross-validate the instrument on independent samples in other Mediterranean and African port systems, confirming the eight-factor structure against more parsimonious alternative models on a larger sample, test its predictive validity against objective performance indicators such as vessel time in port, assess its stability over time, and refine the social performance component — notably by measuring occupational health and safety as a distinct facet — and the analytical-maturity component.

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