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DIGITAL TWIN RESILIENCE IN PORTUGUESE ATLANTIC CORRIDOR PORTS: A STAKEHOLDER STUDY

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Original Article

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ABSTRACT

Digital transformation (DTx) has become a key driver of competitiveness, sustainability, and operational performance in modern ports, where increasingly complex supply chains require resilient information management. Among emerging digital technologies, the Digital Twin (DT) has gained attention as a cyber-physical solution that strengthens information flow resilience and supports smarter port operations.

In line with Portugal's Ports 5+ Strategy, which promotes digitalization and automation as pillars of port modernization, this study examines the potential of DT solutions in Portuguese core ports within the Atlantic Corridor of the Trans-European Transport Network (TEN-T), recognizing information as a strategic operational asset.

The study adopts an exploratory qualitative design based on semi-structured interviews with ten key stakeholders from a core Atlantic Corridor port. The interview protocol focused on two dimensions: (i) information flow resilience and (ii) the continuity and sustainability of port and logistics operations.

The findings indicate that stakeholders perceive DT solutions as having significant potential to improve logistics resilience by reducing vulnerabilities, anticipating disruptions, and maintaining operational continuity during technological failures, congestion, and other unexpected events. However, the study also identifies important research gaps. Existing literature lacks an integrated framework connecting DT with port resilience, interoperability, and logistics continuity, while empirical evidence remains largely limited to major high-tech terminals, with insufficient attention to medium-sized ports and their regional and organizational contexts, such as those in Portugal.

Keywords: *Digital Twin, Information Flow Resilience, Port Operations, Atlantic Corridor, Portuguese Ports, Stakeholder Analysis, Maritime Logistics Continuity*

1. INTRODUCTION

Seaports are strategic components of the global economy, serving as key hubs for maritime and inland freight transport. As nearly 90% of global trade is carried by sea, ports are essential to the functioning and stability of modern supply chains. Their role in facilitating intermodal transport means that changes in port efficiency can generate significant effects across the entire value chain.

Ports also contribute to regional and national economic development (Valenzuela-Silva et al., 2025). Improved port performance can create economies of scale, reduce emissions, and lower transportation costs for businesses (Klar et al., 2023). Moreover, ports constitute critical national infrastructure because they support the continuous supply of essential goods (Epiphaniou et al., 2023).

Port resilience is therefore crucial to overall supply chain resilience. It refers to the ability of ports to anticipate, prepare for, respond to, and recover from disruptions, including natural disasters, public health crises, and technological failures, while maintaining essential operations. Given the highly interconnected nature of maritime logistics, disruptions at a single port can rapidly produce cascading effects throughout the wider supply chain (Tsoulfas, 2025).

1.1. SEAPORT DIGITAL TRANSFORMATION

Digital transformation (DTx), within the Industry 4.0 and 5.0 paradigms, can strengthen port resilience by replacing reactive governance with proactive, data-driven decision-making and predictive intelligence. This shift enables ports to adapt to changing conditions while minimizing severe operational disruptions. In this context, the Digital Twin (DT) has emerged as a cyber-physical solution capable of improving the resilience of information flows in port operations (Guizzardi et al., 2025; Zhou et al., 2021).

DTx involves a systemic transformation of the organization, coordination, and governance of maritime trade and supply chain operations. It integrates technologies such as the Internet of Things (IoT), machine learning (ML), artificial intelligence (AI), and DTs with data-driven management practices. These technologies aim to improve operational efficiency, reduce bottlenecks, strengthen resilience, and support sustainability and decarbonization objectives (González-Cancelas et al., 2025). DTx also repositions ports as coordinators of collaborative networks connecting shipping companies, terminal operators, freight forwarders, customs authorities, and inland transport providers within data-centric ecosystems.

Information therefore represents a strategic operational asset and an intangible infrastructure supporting port resilience and competitiveness (Su, 2026). However, port ecosystems comprise complex and interdependent groups of operational, regulatory, and socioeconomic stakeholders (Cai et al., 2022). Differences in their priorities and perspectives may create conflicting objectives and hinder the implementation of advanced technologies (Homayouni et al., 2025).

In Portugal, port digitalization has progressed through the continuous development of information systems, particularly the Single Logistics Window (JUL). This platform has improved interoperability, simplified procedures, replaced paper-based processes, and extended digital integration across the intermodal logistics chain. It enables authorities and operators to exchange data in real time, reducing administrative burdens and aligning national procedures with European standards (Presidência do Conselho de Ministros, 2019).

More recently, the NEXUS Innovation Pact, funded through Portugal's Recovery and Resilience Plan and led by APS Administração dos Portos de Sines e do Algarve, S.A., introduced improvements to JUL, cybersecurity systems, and autonomous operational capabilities (APS Administração dos Portos de Sines e Algarve, 2022). This process continues under the Ports 5+ Strategy for 2025–2035 (Table 1), which provides €70 million for advanced digital technologies and the full automation of administrative procedures through JUL 5+. The strategy seeks to strengthen maritime and intermodal integration across regional, national, and European logistics networks (Presidência do Conselho de Ministros, 2025).

Table 1. Strategic Objectives of the Ports 5+ Strategy

Strategic objectives	Detailed description
More Investment and Growth	Focus on strengthening private investment to accelerate the increase in port capacity, productivity, and competitiveness. Aims to grow the movement of ships, passengers, and cargo (especially exports), prioritizing the concession model for the private construction and operation of terminals.
More Decarbonization and Sustainability	Focus on the energy transition with public and private investment in electrification (Onshore Power Supply), the supply of green fuels (LNG and hydrogen), and offshore wind energy. Sustainability goals include protecting ecosystems and reducing emissions, integrating circular economy industries.
More Intermodality and Connectivity	Focus on logistics integration to increase rail participation and improve land connections. The investment aims at linking with dry ports and logistics platforms (TEN-T Networks), promoting advances in the fluidity of sustainable flows and reducing the environmental impact on local communities.
More Digitization and Automation	Focus on technological advancements through the evolution of the Single Logistics Window (JUL 5+), artificial intelligence, and terminal automation. The investment in digitalization aims for total interoperability between ships, ports, and land transport, optimizing operational efficiency and data security.
More Integration and Security	Focus on the symbiotic Port-City relationship through the transfer of non-operational areas to municipal management and joint planning. This includes strengthening security against illicit trade through technological investment and fostering strategic cooperation with local communities.

Source: (Presidência do Conselho de Ministros, 2025)

1.2. SEAPORT DIGITAL TWIN

The literature defines a Digital Twin (DT) as a virtual representation of a physical system, process, or object that remains continuously synchronized with its physical counterpart through bidirectional data flows (Guizzardi et al., 2025; Klar et al., 2023; Neugebauer et al., 2024). Within industrial engineering, a DT extends beyond three-dimensional modelling and functions as a dynamic decision-support system that integrates historical data, real-time sensor inputs, and analytical models to predict system behaviour and optimize operations (Fonseca et al., 2023; Giering & Dyck, 2021; Homayouni et al., 2025).

In this study, a port logistics DT is conceptualized as a dynamic and interoperable digital system that maintains continuous bidirectional synchronization with the port ecosystem and its stakeholder network. Through real-time data flows, it supports simulation, prediction, and coordinated decision-making across operational levels.

This definition distinguishes DTs from conventional Port Community Systems (PCS) and platforms such as Portugal's Single Logistics Window (JUL) in three respects. First, while PCS and JUL primarily support data exchange and administrative processing, a DT integrates heterogeneous sources, including Internet of Things sensor data, operational logs, and interorganizational transactions, into a continuously updated virtual model. Second, unlike static or event-triggered reporting tools, a DT incorporates predictive analytics and simulation capabilities, enabling proactive scenario planning. Third, it functions as a decision-support layer that models the interdependencies among physical assets, information flows, and stakeholder interactions, which are not fully represented in the current JUL infrastructure.

Because no operational DT has yet been implemented in the Portuguese Atlantic Corridor ports, this study evaluates its potential through stakeholder perceptions. These perceptions are treated as informed anticipatory judgments based on stakeholders' direct experience with existing digital systems and their knowledge of emerging technological capabilities.

Despite growing interest in DTs, research on their adoption in ports and maritime terminals remains limited and fragmented. While some ports are still developing basic digital capabilities, larger and more technologically advanced ports have begun implementing DT solutions. Their application in small and medium-sized ports remains particularly underexplored (Neugebauer et al., 2024). Four major research gaps can therefore be identified:

- **Theoretical gap:** The literature proposes numerous component-level architectures and models, but lacks an integrated framework linking DTs with port resilience, interoperability, and logistics continuity (Ding et al., 2023; Eom et al., 2023; González-Cancelas et al., 2025; Hakimi et al., 2025; Neugebauer et al., 2023; Zavvos et al., 2024).
- **Practical gap:** Empirical implementations are concentrated in large and often highly automated terminals, leaving unresolved questions concerning adoption, standardization, scalability, and return on investment (Ding et al., 2023; Eom et al., 2023; Hakimi et al., 2025; Neugebauer et al., 2023; Paredis et al., 2024; Yao et al., 2021).
- **Methodological gap:** Existing studies rely heavily on prototypes and isolated demonstrations, with limited use of comparative, longitudinal, or causally oriented research designs (Bao et al., 2024; González-Cancelas et al., 2025; Neugebauer et al., 2023; Yao et al., 2021).
- **Contextual gap:** Most evidence relates to large, technologically advanced terminals in Europe and East Asia, while Portuguese ports, small and medium-sized enterprises, and regional and organizational specificities remain insufficiently examined (Bao et al., 2024; Ding et al., 2023; González-Cancelas et al., 2025; Neugebauer et al., 2023; Paredis et al., 2024; Zavvos et al., 2024).

In line with the strategic priorities of the Portuguese Government, this study examines stakeholder perceptions of the potential of DT solutions in a core Portuguese port located within the Atlantic Corridor of the Trans-European Transport Network (TEN-T). Although the empirical analysis focuses on a single port, the case shares important institutional and operational characteristics with other Portuguese Atlantic Corridor core ports. These include integration into the TEN-T core network, use of the national JUL platform, alignment with the Ports 5+ Strategy for 2025–2035, and the presence of a comparable multi-stakeholder logistics ecosystem. These common features enhance the analytical relevance of the findings beyond the selected case.

Given the complexity of port ecosystems and the divergent operational, regulatory, and strategic priorities of their stakeholders, semi-structured interviews were used to capture heterogeneous views on DT adoption.

The study addresses the following research question:

To what extent do port ecosystem stakeholders perceive Digital Twin solutions as capable of strengthening information flow resilience and operational continuity in medium-sized Atlantic Corridor ports?

The interview data were examined using thematic analysis, which provides a structured yet flexible method for identifying, interpreting, and reporting recurring patterns within qualitative datasets (Ahmed et al., 2025; Braun & Clarke, 2022).

The study contributes to the broader debate on the digital economy by examining DT technology as a practical response to the operational, coordination, and resilience challenges facing maritime logistics in an increasingly uncertain global environment.

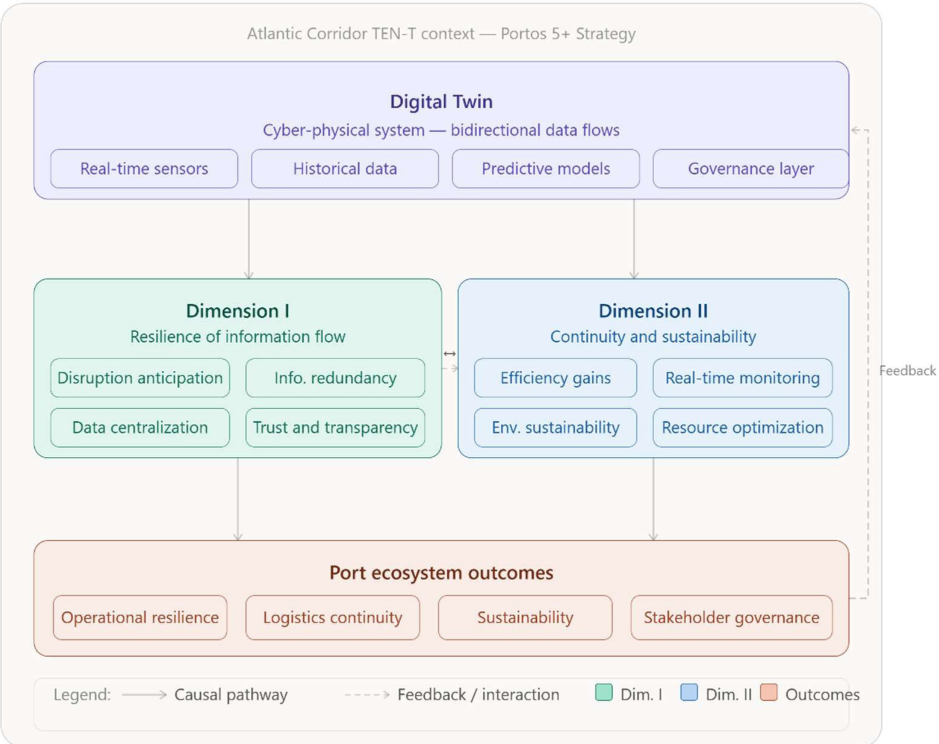
The analytical model conceptualizes the DT as a socio-technical system operating within the port logistics ecosystem through two interdependent dimensions (Fig. 1).

The first dimension concerns **information flow resilience**. DT solutions can support disruption anticipation, information redundancy, the integration of fragmented data, and greater trust and transparency among stakeholders.

The second dimension concerns **the continuity and sustainability of port and logistics operations**. DTs can enable real-time monitoring, improve operational efficiency, optimize resource use, and support environmental sustainability measures.

These dimensions are mutually reinforcing. Resilient information flows are a prerequisite for operational continuity, while sustained operational performance generates feedback that improves the DT's predictive and coordination capabilities. Together, they may produce system-level outcomes such as operational resilience, logistics continuity, environmental sustainability, and collaborative stakeholder governance. These outcomes are consistent with the priorities of the Ports 5+ Strategy and the TEN-T Atlantic Corridor framework.

Figure 1. Conceptual framework: Digital Twin as a sociotechnical enabler of port resilience and operational continuity



Source: Authors

The article is structured as follows: after the introduction, section 2 details the methodology adopted, highlighting the research model, the method, and the sample; section 3 addresses the results and discussion; and finally, the conclusions are presented.

2. METHODS

The study adopts an exploratory qualitative design based on semi-structured interviews with ten key stakeholder representatives. Participants were selected through purposive, expert-based sampling to capture informed perspectives from actors directly involved in port logistics, information exchange, and coordination within the Portuguese Atlantic Corridor port ecosystem. Rather than seeking statistical representativeness, the sampling strategy emphasized informational richness, functional relevance, and stakeholder diversity, in line with exploratory qualitative research.

The participants represented different functional layers of the port-logistics ecosystem, allowing the study to capture heterogeneous views on information flow resilience, operational continuity, digital coordination, and the potential adoption of Digital Twin solutions. Selection criteria included: (a) direct involvement in port-related logistics activities; (b) substantial experience in coordination or decision-making roles; (c) practical knowledge of digital information systems and interorganizational processes; (d) regular interaction with port authorities or Port Community Systems; and (e) strategic or operational responsibility within the participant's organization.

Interviewees occupied senior coordination or management positions and had an average of approximately 20 years of professional experience. Their backgrounds provided substantial knowledge of logistics operations, digital infrastructure, stakeholder coordination, and port-related business processes. Selection also considered participants' operational integration and established collaborative relationships within the port ecosystem. Although access and availability influenced recruitment, the interviews generated detailed operational and strategic insights into resilience, interoperability, governance, sustainability, and disruption management.

The data were analyzed through thematic analysis following Braun and Clarke (2022). The process involved data familiarization, repeated reading, analytical note-taking, initial coding, theme development, theme review, and final theme definition. Codes were grouped into candidate themes based on recurring patterns of meaning, after which themes were assessed for internal coherence, distinctiveness, and consistency with the dataset. Themes were merged, divided, refined, or discarded where necessary.

Data collection continued until thematic recurrence and analytical convergence were observed across the main research dimensions. The final two interviews produced no substantive new themes or perspectives, while the thematic categories associated with both analytical dimensions were consistently supported across different stakeholder types. This indicated an acceptable level of thematic saturation for the exploratory purpose of the study (Guest et al., 2006).

The reporting stage combined illustrative interview excerpts, researcher interpretation, and relevant literature to develop an evidence-based response to the research question. Researcher reflexivity was maintained throughout the analysis, recognizing that themes are interpretively constructed rather than mechanically extracted from the data.

The interview guide was structured around two dimensions: (i) information flow resilience and (ii) the continuity and sustainability of port and logistics operations. To protect confidentiality, participants were coded according to stakeholder typology, as shown in Table 2. Interviews lasted approximately 45 minutes on average, were transcribed, and underwent content clarification and linguistic cleaning while preserving their original semantic meaning. Thematic analysis was then used to identify and organize the principal research themes (Jović et al., 2022).

Before each interview, participants received a brief explanation of the Digital Twin concept as operationalized in this study. The explanation distinguished Digital Twins from existing Port Community Systems and administrative platforms, ensuring a shared conceptual basis for the discussion.

Table 2. Stakeholder codification

Typology	n	Code	Functional Role in the Port Ecosystem
Importer	1	A1	Coordination of cargo reception, customs-related processes, and inbound logistics operations
Exporter	1	B1	Coordination of export logistics operations and international shipment flows
Logistics operator	1	C1	Coordination of logistics activities and collaborative supply chain operations
Logistics operator	1	C2	Strategic logistics and transport management across integrated logistics networks
Land transporter	1	D1	Coordination of inland freight transportation and operational traffic management
Land transporter	1	D2	Management of road transport operations and logistics execution activities
Customs Broker	1	E1	Coordination of freight forwarding, customs procedures, transport logistics, and import/export documentation flows
Customs Agent	1	F1	Coordination of customs clearance procedures and regulatory compliance within import logistics operations
Intermodal Platform	1	G1	Management of rail freight transport, inland terminal operations, and intermodal cargo coordination
Port Dimension	1	H1	Strategic planning, port governance, infrastructure development, tariff management, and innovation oversight

Source: Authors

3. RESULTS AND DISCUSSION

3.1. CASE STUDY

The Trans-European Transport Network (TEN-T) is a European Union policy (Regulation (EU) 2024/1679) that aims to establish a single, high-quality multimodal transport network across Europe. This network comprises infrastructure for rail, road, air, sea and inland waterway transport, as well as associated information and communication technology (ICT) systems and measures to promote the efficiency and sustainability of services. The Core Network (Fig. 2) encompasses the strategically most important parts of the network, focusing on connecting the core ports on the Atlantic coast (Sines, Lisbon/Setúbal and Leixões) to the interior of the Iberian Peninsula and Central Europe.

Figure 2. Map of the Atlantic Corridor (TEN-T)

Source: (Infraestruturas de Portugal, 2021)

The study focused on a Portuguese Atlantic seaport located in southern Europe, recognized for its high cargo throughput, strong international connectivity, and increasing digital maturity. The port plays a strategic role in multimodal logistics chains, exhibiting high levels of technological integration and operational interoperability, thus constituting a relevant context for analyzing the resilience of information flow in complex port-logistics ecosystems.

3.2. ANALYTICAL DIMENSION I- RESILIENCE OF INFORMATION FLOW

An in-depth examination of the responses indicates that DT can greatly enhance the resilience of the logistics ecosystem. This improvement is accomplished by addressing vulnerabilities, anticipating disruptions, and maintaining seamless operations even amidst technological breakdowns, traffic jams, or unforeseen incidents (Table 3).

Table 3. Analytical Dimension I - Main Themes Identified

Themes	Thematic Descriptions
Anticipating Disruptions and Proactive Planning	• Access to statistical and operational data allows for the identification of work peaks, average waiting times, and equipment availability (E1). • Data sharing allows for anticipating problems before they cause greater damage (C1). • Information on congestion, weather, or operational failures allows for rapid reaction and the development of action plans (A1). • Possibility of immediate replanning in the event of a disruption (B1).
Operational Continuity and Information Redundancy	• When systems such as the Automated Customs Declaration Processing System, JUL, or Terminal fail, all stakeholders are left "blind" (F1). • A DT can function as a backup to ensure continuity of information management (F1). • It reduces dependence on individual contacts in the field, making information more reliable and less vulnerable (D2). • Paper is still seen as a contingency, but a robust platform can replace this weakness (F1).
Centralization and Elimination of Fragmentation	• Data sharing eliminates the need to consult multiple platforms and reduces information duplication (D1). • An integrated view improves fluidity and reduces inconsistencies between sources (D1). • It facilitates coordination between dispersed stakeholders (H1).
Strengthening Trust and Transparency	• Shared information builds trust among stakeholders and with customers (C1). • Transparency about the state of operations reduces uncertainty and increases predictability (H1). • Trust is seen as a critical asset in disruptive contexts (C1).
Organizational Commitment and Governance	• Resilience depends on the ongoing commitment of all stakeholders (C2). • Need to designate internal managers to ensure continuity and reliability of information (H1). • Risk of loss of continuity if there is no adequate project management (H1). • The DT must be accompanied by a clear organizational culture and processes (C2).
Responsiveness to Unforeseen Events	• Allows for earlier responses to projects, delays, and other unforeseen events (D2). • Facilitates rapid and coordinated communication between stakeholders. • Reduces the impact of unexpected events by allowing for immediate adjustments (A1).

Source: Authors

Digital Twin solutions can strengthen information flow resilience in several interconnected ways. The most frequently identified benefit is the ability to anticipate disruptions through real-time and historical data. As one participant explained, "Data sharing alone can give us indicators of peak workloads. It can give us average wait times, equipment availability, etc." (E1). Another noted that "information regarding traffic congestion, weather conditions, or failures would allow for a faster response from the various stakeholders and the development of action plans" (A1).

Participants also emphasized the importance of operational continuity during failures of critical information systems. One stakeholder suggested that "it would make sense to have a backup system for information management, because when one fails, the other will 'protect' me" (F1). DT solutions could also improve information consistency by centralizing data and reducing fragmentation and duplication. According to one participant, "Data available on a single platform would eliminate the need to access multiple platforms and prevent the duplication of information" (D1).

A further benefit concerns trust and crisis response. One stakeholder stated that "customers and partners trust us because we strive to capture all the data to provide an information service. Therefore, a system for updating and sharing information is crucial, especially in a crisis context" (C1). Participants also stressed that technological reliability depends on organizational responsibility and collective involvement: "A project like this requires the involvement of all participants. I believe there should be someone designated within the companies to be responsible for ensuring that there is no loss of continuity and reliability of the necessary information" (H1). Information resilience should therefore be understood not only as a technological capability but also as an organizational, collaborative, and strategic capacity.

The findings from Dimension I are broadly consistent with the literature on DT-enabled resilience in maritime environments, while extending it to the context of medium-sized ports. The theme of disruption anticipation and proactive planning supports the proposition by Zhou et al. (2021) that DT systems can function as decision-support mechanisms by combining real-time monitoring with resource optimization. However, this study shows that, in medium-sized Atlantic Corridor ports, anticipatory capacity is perceived less as a product of highly automated terminal intelligence, as observed in large-scale applications such as Yangshan Port (Ding et al., 2023), and more as an outcome of collaborative data sharing among heterogeneous stakeholders operating across fragmented information systems.

The theme of operational continuity and information redundancy reveals a vulnerability that differs from those commonly discussed in technologically advanced terminals. Existing DT applications in large automated ports primarily focus on equipment scheduling, throughput optimization, and dynamic operational control (Bao et al., 2024; Ding et al., 2023). By contrast, participants in this study emphasized the loss of visibility and coordination caused by failures in administrative platforms, including JUL and customs-processing systems. This finding is consistent with Homayouni et al. (2025), who identify data quality and availability as major barriers to sustainable DT implementation. It further suggests that, in medium-sized ports, DT-enabled information redundancy and backup capabilities may represent a more immediate resilience priority than advanced operational optimization.

Finally, the theme of organizational commitment and governance introduces a dimension that remains underdeveloped in predominantly technical DT frameworks (Klar et al., 2023; Neugebauer et al., 2024). Although existing models emphasize sensors, bidirectional data flows, system integration, and predictive analytics, the present findings indicate that information resilience also depends on clear governance structures, assigned responsibilities, stakeholder commitment, and mutual trust. This result supports Homayouni et al. (2025), who identify conflicting stakeholder priorities as a major implementation barrier, but extends their argument by framing organizational governance not merely as a constraint, but as an active enabler of DT-supported resilience.

3.3. ANALYTICAL DIMENSION II- CONTINUITY AND SUSTAINABILITY OF PORT AND LOGISTICS OPERATIONS

Thematic analysis of the interview data reveals that DT can be crucial for ensuring operational continuity, increasing efficiency, reducing risks, supporting environmental sustainability, and encouraging innovation (Table 4).

Table 4. Analytical Dimension II - Main Themes Identified

Themes	Thematic Descriptions
Acceleration, Efficiency, and Continuous Improvement	• Makes operations faster, more reliable, and less error-prone (E1). • Reduces unnecessary steps and simplifies processes, increasing overall efficiency (E1). • Eliminates manual processes and associated errors (B1). • Enables optimization of empty container pick-ups and deliveries (F1). • Paperless processes make operations more sustainable and consistent (G1).
Real-Time Monitoring and Anticipation of Disruptions	• Continuous monitoring of flows allows for anticipating disruptions and adjusting operations (A1). • Real-time data allows for correcting the course of projects and processes (H1). • Management of disruption scenarios becomes more effective with shared data (B1). • Better transportation planning reduces unnecessary and inefficient trips (D2).
Operational Continuity and Risk Reduction	• Reduces dependence on manual processes, but paper is still seen as a contingency (F1). • Data sharing increases resilience by allowing all stakeholders to maintain visibility even in technological failures (H1). • Well-designed digital processes ensure continuity and stability (G1).
Environmental Sustainability and Carbon Footprint Reduction	• Optimization of truck entry/exit times reduces waiting times and emissions (F1). • Emissions monitoring and environmental control become more rigorous (B1). • Sustainability is addressed through three pillars: warehousing, transportation, and carbon footprint reduction (C2). • More efficient flows reduce energy consumption and waste (C2).
Innovation, Competitiveness, and New Business Models	• Promotes innovation and competitiveness (A1). • Collaborative data allows for the development of new solutions and business models (A1). • Data sharing supports strategic decisions and increases adaptability (H1).
Resource Optimization and Loss Minimization	• Allows for better resource allocation and reduction of operational losses (D2). • Optimization of human resources, equipment, and infrastructure (B1). • More efficient processes reduce costs and increase economic sustainability (A1).

Source: Authors

Thematic analysis indicates that the main perceived benefits of DT are greater operational efficiency, improved real-time monitoring, and stronger environmental sustainability. Participants reported that automation would reduce manual intervention, errors, truck waiting times, and container-handling delays, thereby increasing terminal productivity: “The flow of incoming and outgoing containers should be automated at the gates when passage doesn’t require human intervention” (G1). “Continuity and sustainability can be ensured through better management of disruption scenarios, and regular operational control” (B1). “We believe that having a system with information to allocate carbon consumption to each of our expeditions, for example, is a way to work with clients to define more efficient flows and schedules" (C2). "Data sharing is essential to ensure the continuity and sustainability of port and logistics operations, by accelerating administrative and customs processes, reducing both waiting times and costs" (A1). The findings for Dimension II are broadly consistent with the DT literature but also reveal patterns specific to medium-sized Atlantic Corridor ports. Real-time monitoring supports operational continuity, as shown by Ding et al. (2023) and Wang et al. (2024). However, participants emphasized its role in improving interorganizational coordination and reducing information asymmetries rather than enabling fully automated operational control.

The environmental sustainability theme also aligns with Eom et al. (2023) and Zavvos et al. (2024). In the present study, stakeholders focused mainly on indirect sustainability measures, including shorter truck dwell times, fewer empty-container movements, and improved flow coordination. Unlike technologically advanced terminals that use direct emissions-monitoring systems, medium-sized ports may achieve decarbonisation primarily through logistics efficiency.

Finally, the theme of innovation, competitiveness, and new business models reflects the broader strategic role of DT. This aligns with the systematic review by Nurrosyidah et al. (2026), which identified prediction and data-driven decision-making as the second most prominent driver of DT adoption in smart ports, after operational performance. In the present study, stakeholders viewed DT not only as an operational tool but also as a platform for collaborative coordination and adaptive business models. This perspective extends DT beyond individual terminals to the wider port-logistics ecosystem, in line with Cai et al. (2022).

4. CONCLUSIONS

This study examined how Digital Twin (DT) can strengthen information-flow resilience and support the continuity and sustainability of port-logistics operations in the Portuguese Atlantic Corridor. Based on an exploratory qualitative analysis of stakeholders from different functional areas, the findings indicate that operational resilience is perceived as increasingly dependent on real-time visibility, interoperability, collaborative coordination, and predictive decision-making across interconnected actors and digital infrastructures.

The study contributes to the literature by moving beyond a purely technological understanding of DT and positioning it as a sociotechnical enabler of resilience, operational continuity, and collaborative governance. From the stakeholders' perspective, resilient port operations depend on the quality, accessibility, integration, and synchronization of information flows. Shared and interoperable digital infrastructures are therefore perceived as essential for coordinated responses to operational disruptions.

The findings also contribute to research at the intersection of digital transformation, supply chain resilience, and smart port ecosystems. DT-enabled visibility and data integration are perceived as key mechanisms for adaptive decision-making and coordinated disruption management. This extends existing technical frameworks by emphasizing governance, stakeholder alignment, and interorganizational collaboration.

Several practical implications follow. Port authorities and managers should strengthen integration among Port Community Systems, customs platforms, transport operators, and logistics stakeholders to reduce information fragmentation and operational inefficiencies. Investments should prioritize interoperable infrastructures that enable real-time data exchange, predictive analytics, and collaborative decision-making. DT initiatives should also be supported by governance arrangements, organizational capability development, and stakeholder coordination rather than treated solely as technology-modernization projects.

For policymakers, the findings highlight the importance of interoperability standards, integrated logistics platforms, and collaborative innovation ecosystems aligned with the Portuguese Ports 5+ Strategy. Public investment and regulatory support may also facilitate the transition toward smarter, more sustainable, and resilient port infrastructures.

The study has several limitations. Its purposive and partly convenience-based sample involved a limited number of stakeholders closely connected to the selected port ecosystem, restricting the generalisability of the findings. The single-port exploratory design also prevents comparison across different institutional, operational, and technological contexts. Furthermore, the cross-sectional qualitative approach does not capture the long-term evolution or effects of DT implementation.

Future research should compare multiple ports within the Atlantic Corridor and other European logistics corridors. Longitudinal studies could examine how digital resilience capabilities develop over time, while mixed-method research combining stakeholder perceptions with operational and performance indicators could provide stronger evidence of the relationship between digitalization, interoperability, and resilience.

Overall, the findings suggest that the future resilience of port-logistics ecosystems will increasingly depend on integrated digital infrastructures, synchronized information flows, and collaborative decision-making. Within the scope of this exploratory study, DT is therefore perceived not merely as a technological tool but as a strategic enabler of more resilient, sustainable, and adaptive port ecosystems.

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