The importance of interoperability in smart ports

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Digital transformation

Digital platforms, Interoperability, Smart port

Digitalisation is drastically transforming the way ports operate, as they have evolved from isolated physical infrastructures into complex logistics ecosystems characterised by the interaction of multiple actors and modes of transport. In this context, interoperability has become an essential element for progressing towards truly smart ports, capable of managing maritime, rail and land flows in a coordinated way.

Interoperability makes it possible to connect systems, align processes and share information in a structured and secure way, improving planning, decision-making and coordination among the different actors in the port ecosystem.

Beyond its impact on operational efficiency, interoperability contributes to sustainability by optimising flows and reducing unnecessary movements, strengthening system resilience by enabling a more agile response to disruptions. However, its implementation entails significant challenges, both technological and organisational and cultural.

Within this framework, collaborative initiatives such as the TRAMA project demonstrate how interoperability can be addressed in a practical and structured way, laying the foundations for a more integrated, efficient port model that is better prepared to face current and future challenges.

The new era of smart ports

For centuries, **ports** have worked as **physical nodes** of exchange: spaces where goods, people and cultures converge and from which international trade is articulated. Their value laid mainly in their strategic geographical location, their berthing capacity and the infrastructure available for cargo handling.

However, in recent decades the role of the port has undergone a deep transformation. The growth of global trade, containerisation, the emergence of large shipping alliances and the consolidation of complex logistics chains have turned ports into much more than simple physical infrastructure. Today, a port is a highly interconnected **logistics ecosystem** that integrates maritime, rail and land transport, customs services, logistics operators, specialised terminals and multiple public and private stakeholders.

Port competitiveness no longer depends solely on the number of cranes or the depth of its draughts. It increasingly depends on operational efficiency, the ability to coordinate among actors and the speed at which information flows. In an environment of tight margins and growing volumes, intelligent management of data and processes has become a determining factor.

In this context, the concept of the **Smart Port** emerges (BID 2020), closely linked to Industry 4.0 and the growing digitalisation of the port sector. Although there is no single and universally accepted definition, the term usually refers to ports that incorporate advanced digital technologies to optimise operations, improve decision-making and increase sustainability and resilience.

A smart port integrates tools such as:

- Advanced operational management systems.
- Digital information exchange platforms.
- Sensors and the Internet of Things (IoT).
- Data analytics and predictive systems.
- Equipment and process automation.
- Digital twins and real-time simulation.
- Automatic identification technologies (OCR[1], RFID[2], ANPR[3]).
- Artificial intelligence-based solutions.
- Advanced cybersecurity systems.

However, the true intelligence of a port does not lie only in the adoption of technology. A port may have sophisticated systems and still operate in a fragmented manner if those systems are not aligned with processes and with the logistics ecosystem as a whole. The **smart port** requires a systemic vision, which implies integrating maritime operations, terminals, land accesses, rail hinterland, and administrative services within a coherent digital environment. This involves moving from isolated digitalisation by departments or organisations to a coordinated transformation of the entire port system, known as the hyperconnected port.

To achieve this, **digitalisation** or digital transformation in ports is a structural necessity, not an emerging trend. Some factors have accelerated this process, such as the growth in

vessel size and concentration of port calls, increased pressure to reduce port stay times, greater regulatory and documentary requirements, the need for real-time traceability, environmental and decarbonisation objectives, among others.

Manual management or management based on disconnected systems generates inefficiencies that are no longer acceptable. Delays in information exchange can result in congestion at access points, poor resource allocation, operational cost overruns, or loss of competitiveness compared to other logistics nodes.

Moreover, recent global crises (pandemics, geopolitical disruptions, logistics bottlenecks) have highlighted the need for systems that allow scenarios to be anticipated, impacts to be simulated, and agile responses to unforeseen events. This underscores that port resilience is closely linked to the quality and availability of information.

The port as a complex, multi-level ecosystem

Modern ports are much more than modal interchange terminals. They constitute dynamic **ecosystems** where multiple value chains, regulatory frameworks, business interests, and physical and digital flows converge. Their complexity does not stem only from the volume of goods handled, but from the density of relationships generated among the different actors involved in each operation. Understanding this complexity is essential to understand why digital transformation in the port sector cannot be approached in isolated or in a fragmented way.

One of the defining features of the port environment is the coexistence of a wide diversity of actors, each with specific functions, responsibilities and objectives. The main participants in the port ecosystem include: port authorities, terminal operators (containers, bulk, vehicles, general cargo), shipping lines, shipping agents, logistics operators and freight forwarders, stevedoring companies, road hauliers, rail operators, customs authorities and border inspection agencies, auxiliary service companies (tugboats, pilots, mooring services, bunkering), shippers and importers/exporters, among others.

Each of these actors participates in different phases of the logistics process and handles specific information that is critical to the overall operation. However, their interests are not always aligned. While a terminal may prioritise efficiency in the use of its resources, a shipping line may focus on minimising port stay time, and a haulier on optimising access and exit times.

This diversity generates a network of mutual dependencies where a lack of coordination can have cascading effects. The port therefore does not operate as a single hierarchical organisation, but as a distributed system where coordination is a key element.

Furthermore, the complexity of the port ecosystem is intensified by the convergence of **maritime**, **land** and **rail** operations, each with its own requirements but deeply interdependent. In the maritime domain, the arrival of a vessel requires advance planning of berths, resources and operational sequences, while in the land dimension thousands of trucks depend on transport orders, access slots and validations to avoid congestion. Additionally, there is the rail mode, which operates with rigid time windows and predefined capacities,

requiring proper track allocation, train composition and synchronisation with maritime and road activity. In this multimodal environment, any mismatch in one mode immediately affects the others, making fluid communication, real-time information exchange, and coordination among all actors an indispensable requirement to ensure efficiency, safety, and operational continuity.

In such a highly complex environment, **misaligned digitalisation** among actors can lead to strong digital fragmentation, where each organisation adopts its own tools without ensuring interoperability. This results in data duplication and inconsistencies, delays in status updates, manual processes to reconcile systems, dependence on emails or unstructured documents, and limited overall visibility of operations. Instead of providing efficiency, this disconnected digitalisation transfers complexity from the physical domain to the digital one and also hinders the adoption of advanced solutions such as predictive planning, real-time simulation or intermodal optimisation, which require coherent, integrated and shared information among all actors.

Digital platforms in the port environment

The diversity of actors coexisting in the port ecosystem is reflected not only at the organisational and operational level, but also at the technological level. Each participant in the logistics chain has its own tools or digital platforms designed to optimise internal processes and respond to specific needs. This technological reality reflects the multi-level complexity described above, the port is not a single entity, neither is its digital environment.

Container terminals, for example, operate through advanced management systems known as **Terminal Operating Systems** (TOS), which plan, execute and monitor berth, yard and gate operations. These systems manage resource allocation, container location, vessel loading and discharging sequences and coordination with road and rail transport. They are, in essence, the digital operational core of the terminal.

In the rail domain, **rail operators** and inland terminals use specific platforms for train planning, track allocation, convoy composition, and the management of wagon movements and intermodal units.

Shipping lines, for their part, manage their calls and operations through proprietary systems that integrate fleet planning, onboard space management, transport documentation and global route coordination. These systems interact with shipping agents and terminals to ensure that information related to stowage plans, load and discharge lists or operational incidents flows accurately.

Added to this are **customs** and border inspection systems, which manage declarations, authorisations, controls and regulatory validations. The regulatory dimension introduces an additional layer of digital complexity, as information must comply with strict legal requirements and remain aligned with national and international regulatory frameworks.

Road hauliers and logistics operators also have their own tools, ranging from fleet management systems to route planning and delivery control platforms. Likewise, **shippers and importers** work with corporate management systems, commonly integrated into ERP

platforms, which record orders, inventories, billing, and cargo tracking.

The result is an environment where **multiple platforms** coexist, each optimised for a specific domain, but which need to constantly exchange information for the logistics chain to work efficiently. The container that arrives at the port is not just a physical unit, but also a set of data that must travel between different systems throughout its operational life cycle.

In this context, platforms emerge that are designed not to manage a specific operation, but to facilitate communication and structured information exchange among the different actors. Among these are **Port Community Systems** (PCS), which act as integration hubs within the port community. These platforms make it possible to centralise and distribute messages, coordinate documentary processes, and provide shared visibility over certain operational milestones. Their function is not to replace the internal systems of each organisation, but to connect them so that the flow of information coherently accompanies the physical flow of goods.

What do we mean by interoperability?

This technological reality raises fundamental questions about how to ensure coherence, consistency, and fluidity in information exchange. This is where the concept of interoperability takes on a practical and strategic dimension, becoming the element that enables the transformation of a collection of individual platforms into a truly integrated digital ecosystem.

The coexistence of multiple digital platforms in the port environment makes it clear that digitalisation alone does not guarantee systemic efficiency. For the ecosystem to function as a coherent whole, it is necessary for the different systems, actors and processes to be able to communicate, understand each other and coordinate in a structured manner. This principle is summarised in the concept of **interoperability**, which can be analysed from different complementary dimensions (European Commission 2017).

Technical interoperability refers to the ability of technological systems to exchange data automatically, securely, and in a structured way through common standards and protocols, such as REST APIs. It involves the use of compatible interfaces, recognised messaging formats, and architectures that allow integration between heterogeneous platforms. Without this technical basis, communication between systems depends on manual solutions or specific adaptations that create rigidity and increase maintenance costs.

Semantic interoperability goes one step further and addresses the need for exchanged information to have the same meaning for all participants. It is not enough to transmit data, it is essential that concepts such as container status, customs authorisation or operational availability are interpreted uniformly. The absence of a common language or shared data models can generate inconsistencies that directly affect decision-making and coordination among actors.

Organisational interoperability focuses on the alignment of processes, responsibilities and business rules among the different entities operating in the port. It implies that information flows are integrated into coordinated procedures and that there is clear

governance regarding who generates, validates and consumes each data element. These information flows, which were traditionally carried out through means such as fax, telephone or email, must now be translated into a digital format.

Finally, it must be ensured that information exchange and process digitalisation comply with existing regulatory frameworks, including security regulations, data protection, and international transport standards. Legal compatibility is essential to ensure that digital transformation does not generate compliance risks or regulatory barriers that limit its adoption.

Interoperability as an enabler of the smart port

The real worth of interoperability emerges when analysing its impact on the overall working of the port ecosystem. In an environment characterised by a diversity of actors, multimodality, and competitive pressure, the ability to integrate systems and processes becomes a multiplier of **efficiency**, a facilitator of **sustainability** and a pillar of operational **resilience**.

Operational efficiency in a port depends on real interoperability among all systems that manage maritime, rail and land flows. When these platforms share structured and real-time information it becomes possible to anticipate arrivals, adjust resources, coordinate rail windows, and avoid congestion at land access points. Removing duplication and manual validations improves documentary consistency and reduces waiting times, while the integration of historical and operational data enables the application of predictive tools and optimisation algorithms that transform isolated decisions into data-driven decisions. The result is higher productivity, shorter vessel turnaround times and more efficient use of critical infrastructure, which translates into lower operating costs and greater port competitiveness.

Interoperability directly contributes to port **sustainability** by optimising coordination between transport modes and reducing operational inefficiencies that generate unnecessary emissions. When maritime, rail, and land systems share information in real time, intermodal planning is facilitated, empty movements are minimised, waiting times are reduced, and resource allocation is improved. This integration makes it possible not only to reduce energy consumption and the carbon footprint associated with daily operations, but also to consolidate reliable environmental data to measure performance and move towards evidence-based decarbonisation objectives. Sustainability therefore does not depend only on equipment electrification or the use of alternative fuels, but also on the ability of the digital ecosystem to coordinate efficiently.

Interoperability also strengthens port **resilience** by providing cross-cutting visibility and reaction capacity in the face of operational disruptions. Structured data integration among actors allows incidents to be detected more quickly, resources to be redistributed, and operations to be rescheduled in a coordinated manner, reducing the impact of delays or external interruptions. An interoperable environment also facilitates the implementation of shared contingency plans and scenario simulation, improving preparedness for health

crises, climate events, or disruptions in global supply chains. In this way, resilience ceases to depend only on the physical robustness of infrastructure and also relies on an integrated and adaptable digital architecture.

Current challenges to achieving true interoperability

Although interoperability is presented as a key element for the efficiency, sustainability and resilience of smart ports, its effective implementation is far from simple. The transition from partially digitalised environments to fully integrated ecosystems involve overcoming a series of **structural, technological and organisational challenges**.

One of the main obstacles is the coexistence of **legacy systems**. Many port actors operate with platforms implemented decades ago, designed for specific needs and with closed architectures that hinder integration with more recent solutions. Updating or replacing these systems requires significant investment, careful planning and operational risk management, which slows down digital transformation processes.

This technological limitation is compounded by the **heterogeneity of standards and data models**. Although there are widely used frameworks and formats, not all actors adopt them uniformly, and in many cases local adaptations are developed that generate semantic divergences. The lack of a fully shared common language complicates process automation and makes it necessary to maintain manual validation or information reconciliation mechanisms.

The **organisational dimension** is another significant challenge. Interoperability requires trust among actors who, in many cases, maintain competitive relationships or divergent interests. Sharing strategic information can generate reluctance, especially when there is no clear governance regarding data use, ownership and protection.

Cybersecurity is also a critical factor. As the level of interconnection between systems increases, so does the exposure to digital risks. An interoperable environment must incorporate robust protection mechanisms, authentication and access permissions that ensure the integrity and confidentiality of exchanged information. Trust in system security is an indispensable requirement to encourage the participation of all actors.

Another significant challenge lies in **data quality**. Interoperability amplifies both the value and the errors of shared information. If source data are not reliable, coherent and up to date, their integration can propagate inconsistencies throughout the entire logistics chain. Data governance, the definition of responsibilities and the implementation of validation mechanisms therefore become strategic elements.

Finally, the transformation towards a fully interoperable environment requires advanced digital capabilities and a profound **cultural change**. It is not just about connecting systems, but about redesigning processes and adopting a mindset oriented towards collaboration and transparency. This implies training, organisational adaptation and strategic leadership.

Only by addressing these challenges in a coordinated manner is it possible to consolidate

truly smart ports that are prepared to meet the demands of contemporary global trade.

Port initiatives towards interoperability

The challenges associated with interoperability in the port environment cannot be addressed in isolation by each actor. They require collaborative approaches that bring the port community together around a shared vision of digital transformation. In this context, the **TRAMA** project (Optimisation of the TRAffic MAnagement and infrastructure capacity in the port of Valencia) (Fundación Valenciaport 2024), co-funded by the European Commission, is framed as an initiative aimed at advancing towards greater operational and digital integration of the port and logistics ecosystem.

The **main objective** of is to drive the digital transformation of the port ecosystem by strengthening interoperability among platforms and actors, facilitating more efficient, sustainable and resilient management of logistics flows. This overall objective is translated into specific goals such as the upgrading and evolution of key operational systems, improved multimodal integration between the port and inland terminals, and the strengthening of structured information exchange mechanisms among participants in the port community. In addition, the different platforms must be integrable with national logistics platforms.

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