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Port Automation and Smart Ports: Operational Intelligence and the Application of the UNE 178110:2024 Standard Within the Framework of Smart Cities

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ABSTRACT

To view port automation at the present day simply as being about cranes and the application of technology would be to totally misrepresent what is occurring in today's leading-edge ports. In reality, something much greater than mere technology is happening; there is a complete transformation. Today, the port has evolved into a networked environment through which data flow, stakeholders' coordinated actions are executed, and decisions can now often occur virtually in "real-time."
This paper will trace that transition from the use of automation for tasks and terminals to configurations of the port which operate with systemic logic.
The research draws upon recent scientific publications, technical documentation, and existing legislation. Based on this foundation, the paper will assess four aspects that are invariably interrelated; namely, operational intelligence, data governance, sustainability, and the functional relationships between the port and the smart city. The UNE 178110:2024 standard occupies a specific position within the study for reasons other than its regulatory status; i.e., because it provides a defined framework by which port digitization can be linked to the underlying principles of developing smart cities.
In addition to identifying the advantages associated with such transitions from a strategic perspective (i.e. the competitive advantage associated with becoming a smart port), the paper will identify the challenges that emerge once these transitions move to daily operations. These include technological barriers, organizational resistance, regulatory requirements and institutional coordination. Each of these factors necessitate a new paradigm for viewing the port; i.e., not solely as an infrastructural logistics tool but as an integral participant in regional planning, sustainable urbanism, and competing effectively in the global transportation system.

1. Introduction.

Ports continue to be critical assets for an economy, land use/urban planning, sustainable development and disaster risk reduction/resilience for all coastal urban areas; over 80% of world trade continues to move by sea. While the percentage may seem familiar, it is always good to repeat this fact because it helps to explain why there is such great interest in ports today (i.e., increased traffic, increased concentration of flow, increasingly stringent environmental regulations) and why there is a significant transformation underway in how ports are governed and operated [1,2].

This transformation is often associated with automation and digitalization. The rationale for this association is reasonable: improved port productivity/effectiveness should result in higher levels of terminal efficiency and competitiveness. However, this association has also resulted in a broader and more transformative approach to port management. Smart ports represent a new paradigm that includes advanced digital technologies, collab-

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orative governance arrangements, and sustainability initiatives and approaches based on the smart city model [4-6].

Organisations such as UNCTAD, the OECD and the World Bank have long been insisting that port systems need to be modernised to tackle problems that can no longer be put off: climate change, disruptions in supply chains and increasing logistical complexity. The European Commission has moved in the same direction with policies that establish the port as a smart hub within the trans-European networks [1–3].

This is the context of this study. Its aim is to analyse how port automation has evolved towards the smart port model, focusing on two aspects that are rarely examined together: operational intelligence as the backbone of the smart port, and the UNE 178110:2024 standard as a tool for coordination between ports and smart cities.

2. The Global Context of Port Transformation.

Globalisation and the interdependence of supply chains have increased the operational complexity of ports to levels that few would have anticipated three decades ago. A growing number of larger vessels, fewer and larger ports due to increased corporate concentration, and a trend toward fewer port calls, all have placed additional burden upon existing transportation infrastructures in many areas. That burden has been further exacerbated by the effects of climate change on transportation; increasing sea levels, increasingly common severe storms, and government regulations to decrease emissions associated with maritime transportation, all affect the operational environment at the Port. The Port's role extends beyond being merely a place of commerce; the Port now acts proactively in the area of both sustainable practices and regional resilience [1-2].

The literature also has recently enhanced (and transformed) traditional concepts of Port Competitiveness. For years, traditional measures included only physical parameters such as the availability of water depth, the amount of quayside storage available, and the number of cranes. Those measurements continue to be important today. However, there are new elements to consider. Today's measure of Port Competitiveness also includes the ability to connect into Digital Ecosystems, provide timely access to data/information, and effectively coordinate among multiple public and private entities. Hence the renewed interest in governance models based on data, interoperability and institutional cooperation [2,4,5].

The concept of port automation is not new in the literature. The earliest, more narrow formulations focused almost exclusively on container terminals and three variables: productivity, costs and workplace safety. Over time, the focus broadened to include terminal management systems, automatic identification and remote control of equipment [4–6].

One point bears emphasising. Much of that initial automation developed piecemeal, without an overarching plan. The consequence is well documented: 'technology islands' with virtually no interoperability between them, local optimisation rather than system-wide optimisation, and a persistent disconnect from land and urban transport modes [4–6].

The roll-out of the IoT, cloud computing and big data analytics from 2010 onwards marked a qualitative leap forward. Since then, the literature has drawn a clear distinction between automated ports and smart ports. The latter are not simply 'more automated', but incorporate a systemic approach: data is not a by-product, but the basis upon which decisions are made [4–6].

The term 'smart port' itself originated by analogy with 'smart city'. From this, it draws principles such as technological integration, sustainability, and a focus on the user and the local area. ESPO and PIANC, amongst others, have helped to shape the concept through reports and technical guidelines [4,5,9].

The academic perspective has been particularly useful in challenging a certain naive interpretation of the phenomenon. Smart Ports are more than just machines attached to sensors — they represent Socio-Technical Systems (STS), composed by Digital Platforms, Regulatory Frameworks, Governance Models, and Physical Infrastructure [4,5].

Thus, from this point of view, the Port Transformation represents both an Organisational and Institutional (Governance) issue as well as a Technological challenge.

In the Literature, the Five main Dimensions of the Smart Port can be identified as follows: Operational Efficiency; Environmental Sustainability; Security & Resilience; Logistics Integration; Urban Environment Connection. As we will see below how each dimension is viewed may have a great impact. They do not exist in isolation. They are interdependent and require Multidisciplinary Approaches if a significant Progress is to be achieved [5,9].

Although there is a considerable amount of Research being carried out on Smart Ports, there are still two Gaps worthy of mention. The First one refers to the lack of Analysis of Specific Regulatory Frameworks which allow for the Integration between Smart Cities and Ports. Although UNE 178110:2024 has been widely referenced in recent years, there has been very little Academic Interest shown towards this Standard and the Value that it represents as a Tool for Aligning the Digitalization of Ports with Smart City Strategies in Spain and Europe has not yet been fully explored [5,10,12].This article seeks to push in that direction [4,6,10].

3. Port Automation: Technological Developments and Models.

Automation is one of the cornerstones of the modernisation of the port system. It has not been rolled out out of a technological imperative, but rather to address specific challenges: improving efficiency, cutting costs, enhancing workplace safety and handling increasingly complex operations. Unlike other industrial sectors, its trajectory has not been linear. It has advanced in fits and starts, shaped by technological, economic, social and regulatory factors that did not always pull in the same direction [2,6].

Viewed from a historical perspective, it should be understood as a succession of stages in which mechanical, electronic and digital technologies have progressively overlapped. The process has now reached a stage of maturity where the interesting question is no longer how much more we can automate, but how we integrate what we have and how we manage increasingly technified infrastructures [2,6].

3.1. *First Phase: Mechanisation and Basic Automation.*

The initial period is characterized by the mechanical treatment of commodities. Containers adopted widely from the mid-20th century dramatically changed the landscape. Quay-side productivity and time to operate increased with the installation of gantry-crane, mechanical transportation of commodities within terminals and specialized machinery; as did efficiency. That nearly all automation was physical. Nearly all integrated systems relating to information (i.e., IT) were cosmetic. And most often planning was based on employee knowledge/experience. Nevertheless, this was an important phase. Standardization of commodity flow and procedure was established during this period and provided the foundation for what followed [2,7].

3.2. *Second Phase: Digitisation of Terminal Management.*

Terminal Operating Systems (TOS) signalled the beginning of something entirely new. For the very first time, operations such as the loading/unloading of containers, storage of the container, and allocation of resources could all be managed through a single platform; [6,8]

This is true when it comes to the potential for increased coordination and management in terms of planning. However, there is complete agreement regarding one key element of both TOS and its implementation – namely that, originally, most TOS systems were operated in a "closed" manner. As such, communication with the remaining stakeholders within the overall logistics/supply chain model – shipping companies, railways operators, customs officials etc., was extremely limited. Therefore, this lack of communication resulted in less than optimal use of overall potential for improving the efficiency of the entire port system. At present, TOS remains a critical element in modern digital architecture of ports, yet the original limitations placed upon them are being addressed via new solutions; [6,8].

3.3. *Advanced Automation and Semi-automated Terminals.*

The 2000s brought remote control, sensors and positioning systems, and with them the first semi-automated terminals. In these environments, automated stacking cranes (ASC) and automated guided vehicles (AGV) operate with a high degree of autonomy, although always under human supervision from control centres [6,7].

Empirical studies agree that the model delivers clear improvements in productivity and safety, partly because it removes staff from the most hazardous environments. However, the picture is not entirely clear-cut. Initial investments are high, maintenance is complex, and staff with specific skills are required—a profile that is not always easy to find [7,17]. The World Bank and UNCTAD have pointed out that advanced automation is not a one-size-fits-all solution: it depends on the context of each port—traffic volume, type of cargo, operational model, governance structure—[2,6].

The technical literature generally identifies three types of models according to the level of integration reached [4;7]:

Automated ports with selective automation. Automation is only applied to some procedures or devices, so as to constitute a single system. It is a frequent situation in medium-sized harbors and in those of reduced budget.

Semi-automatic berths. They associate automatic actions with direct interventions from man. It represents the prevailing solution today because it achieves a good compromise between efficiency and operability.

Totally automated berths. They operate with a very important degree of independence, with very few human interventions in manual activities. They are the technological limit of what currently exists in terms of automation, but their application is constrained due to the high cost, organizational complexity, and risk involved in the change process. These models do not exclude each other. In many harbors they coexist inside the same area, which implies a necessity for effective coordination mechanisms and integrated management.There are several studies that highlight that the structural limits that automation cannot fully eliminate, such as the lack of coherence among systems and interoperability problems, the local optimization of parts with respect to the total, low connectivity with urban and regional systems, and the reduced ability to react to unpredictable events [4; 6; 7].This is why both research and practice are being oriented toward more globalized forms of automation, centered around the concept of operational intelligence and in real time [4; 6], there is also a significant discussion going on related to the relationships between automation and sustainability.

Automation can contribute to reducing emissions — through the optimization of the operations, electricization of equipment, improvement of energy efficiency — but it also generates discomforting questions concerning employment, social acceptability and the governance of the changes [17; 18].

As stated by the O.E.C.D.: port automation will be acceptable if we adopt a strategy of broad sustainable transition that includes training, social dialogue and innovative inclusion [17]. In conclusion, automation is a necessary, but not sufficient, requirement for developing smart ports. To reach the smart port model it is necessary to abandon the logic of equipment or processes isolated and assume a systemic view based on data, interoperability and collective governance [4; 5; 6].

Seen under this angle, automation represents one of the technological bases of the operational intelligence [4;6].

4. Smart Ports: Digital Architecture, Governance and Sustainability.

To speak of a smart port is to speak of something different from an automated port. And the difference is not merely semantic. Digitalisation ceases to be a collection of isolated solutions and becomes an architecture that links infrastructure, processes, stakeholders and data. The starting point is relatively simple: the port is a socio-technical system, embedded within global logistics networks and, at the same time, within its urban environment [4-6].

Compared to the conventional model, what defines a smart port is not the extent of automation, but how information is managed, how decisions are coordinated among multiple stakeholders, and what objectives the system as a whole is geared towards. Sustainability, resilience, public value. Three pillars serve as the main drivers of the smart port: digital architecture, governance and sustainability [4,6,9].

4.1. Digital Architecture.

The four basic elements of the architecture of a smart port are interoperability, scalability, modularity and security. These elements are not simple; they allow the integration of various systems (heterogeneous), the possibility of evolving technology while continuing operations uninterrupted, and ensure the safety of data and key assets [6,8,10] . The transition from monolithic structures to multi-layered structures with interaction via standardised interfaces and interoperable services has been well documented in the literature [6,8].

From a conceptual standpoint, the digital architecture of the smart port may be considered as a five-layer structure. Layer one is the physical and sensing layer which combines all automation technologies with IoT networks to capture operating conditions and environmental data. Layer two is the communication layer, responsible for transmitting data securely and in real time, using wired and wireless and 5G networks. The third layer is the layer of data management and processing where the advanced analytical and AI platforms will reside. Layer four is the application and service layer providing decision support tools. Layer five is the layer of external integration, designed to interoperate with other urban systems and logistics operators [6,8,10]. The advantages of organizing it in such a manner are practical: each new functionality can be added without having to redo the entire system.

4.2. Governance.

Governance is arguably the most sensitive aspect of the smart port. Sensors, automation systems and platforms do not resolve the underlying issue, which arises first: who makes decisions, based on what information, under what rules, and with what degree of coordination between stakeholders. Port management has operated for decades on hierarchical models, with reasonably stable divisions of responsibility between port authorities, private operators and public administrations [4,6,10].

The smart port puts strain on this division. It does not break it, but it forces it to evolve. Every decision affects the rest of the system: the neighbouring terminal, land traffic, the city, energy consumption and security. That is why the smart port model calls for more collaborative forms of governance, underpinned by coordination between stakeholders and the exchange of information in near real time [6,10].

ESPO has stated clearly in relation to this: smart governance is not an add-on to digitalization; it is a precondition for digitalization to work. A lack of coordination will lead to technology investments resulting in dis-integrated systems, duplication, and additional friction [9]. Collaborative digital platforms have a central role in addressing these challenges. And in their most advanced form, Port Community Systems (PCS) have already incorporated urban stakeholders – mobility authorities, energy managers, emergency responders, local government etc. who were formerly outside the system's purview [8, 13].

Managing data represents another significant challenge. Collecting information is insufficient. There must be clear definitions of responsibility, as well as standards of quality, traceability and access/use/reuse rights. Digitalization has turned cybersecurity into a strategic factor and not just a technical one because of the critical nature of port infrastructure [6, 8, 11]. The ISO-based frameworks also suggest integrated approaches to managing risks associated with digital technologies that include technical, organizational and training components [6, 11].

4.3. Sustainability as a Strategic Priority.

The "Sustainable Port" concept is now at the center of all port development initiatives. Increasing regulatory obligations; increasing public pressure for sustainability; and increasing demands by companies (through their CSR policies) for sustainable supply chains have led to increased scrutiny of how we operate our ports. Digitalization represents a valuable tool to optimize consumption, reduce emissions and enhance resource management when executed correctly [9, 18]. A "Smart Port" uses environmental monitoring systems to measure factors like air quality, energy usage, noise levels and emission rates. This enables decision making based upon data-driven insights versus intuitive assumptions [9].

Port Sustainability however encompasses much more than just environmental concerns. There is also an economic component related to operational efficiencies and resiliencies: a port that anticipates disruptions, reallocates resources, adjusts capacity due to variability in demand will save money and gain competitive advantage. The OECD stated it directly: digitalization of ports within sustainability strategies could create economic value without compromising either environmental or societal goals [9].

There is also a social aspect that many technical assessments neglect: the social implications of automation – i.e., job displacement, vocational education/training, organizational culture changes and the port's relationships with its city. Without transparent stakeholder involvement and open communication regarding the public aspects of digital transformations, digital transformation cannot occur with legitimacy [14-17].

Digital architecture, governance and sustainability do not exist independently. These concepts are interdependent. Architecture presents tools to achieve solutions; governance makes decisions on how to utilize those tools; sustainability defines the strategic direction toward which those tools and decisions should lead. When those three dimensions are sufficiently integrated, the "smart port" becomes a platform for local/regional innovation, improving its internal processes while influencing its local community, regional logistics, the environment and urban planning [4,6,9].

5. Operational Intelligence and Advanced Systems.

The common misconception concerning port digitization is that there are many new pieces of data; sensors, automated equipment, internal management systems, and third party platforms etc., therefore when all this information is available it will make better decisions. The problem is not true. More data does not mean more knowledge. Operational Intelligence is designed to bridge that knowledge gap for what you know and what you need to know about your business [6, 8].

Smart Ports can define operational intelligence as the ability of the port system to process disparate sources of data, analyze that data in real-time and make decisions on how to operate better, anticipate potential problems or identify opportunities to create value through its interaction with outside city logistics, administrative systems etc. [6, 13].

5.1. Conceptualisation in the Port Sector.

The term "operational intelligence" was coined by Gartner to describe the ability of organizations to generate insight and make strategic decisions based upon their operational performance in near real-time using Advanced Data Analysis, Artificial Intelligence (AI), and Modeling. Unlike Business Intelligence (BI) where an organization views historical data, operational intelligence views current data in real-time to enable the organization to respond quickly to emerging issues [6, 8].. As defined by Gartner, there are three main areas that comprise operational intelligence. Those areas include observation, through the ongoing collection of both operational and environmental data; analysis, utilizing algorithms to identify trends, anomalies and patterns within the collected data; and decision-making, through systems that provide recommendations or automatically execute responses [6, 10].

Port data includes vessel movement data, loading/unloading activity data, equipment utilization data, turnaround time data and cargo flow data. By integrating all this information together into a single database, a port gains a complete picture of how its operations are functioning. Ports can also identify potential bottlenecks and opportunities for improvement in operations. Without proper integration of such disparate databases, those same issues may remain undetected [6, 8]. Environmental data — air quality measurements, noise levels, emissions, energy consumption — allows ports to measure the full impacts of its activities on the surrounding community. It provides an additional means for measuring compliance with regulations while providing a metric to track progress toward quantifiable sustainability goals [9, 18].

When external data sources are included in operational intelligence — including but not limited to land transportation network data, urban mobility platform data, customs data and other connected logistics related data — it becomes increasingly important to coordinate goods flows and reduce congestion impacts on the surrounding community [13, 14]. Using machine learning and predictive analytics, ports can anticipate demand, optimize resource utilization and recognize anomalies prior to them becoming significant operational problems. Evidence indicates that many smart ports have experienced improved punctuality as well as reduced wait times for ships and trucks, resulting in higher overall productivity [6,8].

A second layer of capabilities exists when artificial intelligence (AI) is added to the previous layers of capabilities. With AI, the complexity associated with making certain types of decisions can be automated while allowing the port's system to adapt to changing conditions in the port's operating environment. Smart ports currently utilize AI-based solutions to predict arrival times and possible congestion events, optimize the placement of containers stacked in yards, perform predictive maintenance on equipment, and monitor for security threats as well as cyber threats [6, 16]. However, the OECD has been very cautious about AI in critical infrastructure. The OECD believes that if AI is going to be effectively implemented at a port then the governing framework will need to establish clear guidelines regarding transparency, traceability and reliability. These are not merely nice-to-haves. Rather, they are required to foster trust in systems that ultimately drive the port's operation and affect potentially sensitive decisions [16].

One of the most powerful examples of advanced AI tools is digital twin technology. A digital twin represents a dynamic virtual image of a physical entity (such as a port). Digital twins allow simulation studies to be conducted. Decisions can be evaluated using digital twins. Investments can be planned with increased confidence. Furthermore, when digital twins are linked to urban systems they begin to lose their association solely with ports. Instead they can be used for urban planning [14].

5.2. Operational intelligence and resilience

The adoption of resilience into the Port Agenda is being driven by recent global supply chain disruptions. Operational Intelligence supports this by identifying potential vulnerabilities, anticipating failure, coordinating response efforts during crisis events [1,2,6] and real time analytics/scenario simulation support the ability to model (assess) the impacts from extreme events (adverse weather conditions, logistics disruptions, traffic congestion etc.) and provide for more targeted response activities [6,18].

Implementing Operational Intelligence can be challenging. The common barriers to implementation are: data quality and availability; interoperability issues related to use of multiple system platforms; data protection requirements; and employee education/training needs [6,8]. As stated by UNCTAD in numerous reports overcoming such barriers requires an integrated approach. Purchasing technology alone will not meet the challenges facing ports. In addition to purchasing technology sustained investments of resources (people & dollars), developing requisite professional skills, establishing the appropriate governing structures/rules & regulations that support the changes are all required [1,6,17].

Therefore, Operational Intelligence cannot simply be seen as one additional layer of technology supporting operations. It must be considered a cross cutting element which integrates automation, digital architecture/governance and operational decision making with strategic business objectives [6,8,10].

6. UNE 178110:2024: Regulatory Analysis and Implementation.

Smart ports, as part of the broader digitalization process toward a "smart" model, raise issues that cannot be resolved by an engineer or manager (alone). Governance, interoperability, security, sustainability, and assessing maturity for each of these areas require common platforms. Digitalization will proceed via separate solutions that are difficult to scale and typically non-interchangeable with others absent a common platform for references [10-12].

UNE 178110:2024 is the principal regulatory framework governing the development of Spanish smart ports. The value of the framework is two fold. Not only does it provide a technical basis for digital transformation; its most important aspect is defining the relationship between smart ports and smart cities. As part of the UNE 178100 Smart Cities Family, UNE 178110:2024 applies the principles established for the urban environment to the port sector which has highly complex operational processes and an infrastructure of great strategic relevance [10,13].

6.1. General Framework of the UNE 178-100 Family.

The UNE 178-100 family, developed by AENOR, provides a common framework for the development of smart cities in Spain. It addresses governance, interoperability, data management, sustainability and evaluation using indicators [10–12]. UNE 178-100:2024 is part of this framework to ensure consistency between smart port systems and smart city platforms, a consistency that is particularly critical in metropolitan ports, where port decisions have a direct impact on mobility, the environment and urban quality of life [10,13].

6.2. Scope, Objectives and Structure.

The standard sets out requirements and guidelines for the design, implementation and evaluation of smart ports. Its main purpose is to facilitate the digital transformation of the port system through a structured approach based on three pillars: interoperability, scalability and sustainability [10]. Its specific objectives include proposing a reference architecture, establishing criteria for governance and data management, and incorporating sustainability and resilience as strategic pillars. The standard avoids imposing specific technologies. It advocates a flexible framework, adaptable to the operational, institutional and territorial realities of each port [10].

The emphasis on clear and participatory governance models runs throughout the text. Well-defined roles, explicit responsibilities, coordination mechanisms, genuine public-private cooperation, and close links with urban and regional authorities [10,13]. Furthermore, the choice of a reference architecture geared towards interoperability, with open standards and modular platforms, is in line with the approach that international bodies such as ISO have been advocating for critical infrastructure [11,12].

The role of data management is at the core of this standard. This standard outlines principles relating to quality, security and reuse of all data created at or through the port, and it also emphasizes that there are certain guidelines related to data governance that should be established: who owns the data; what access exists to the data; how will personal data be protected; how will cybersecurity be maintained; and under what conditions can the data be reused. If these principles do not exist, then the opportunity for operational intelligence disappears [6,10]. Sustainability has been included as a crosscutting theme, in harmony with the Sustainable Development Goals and the EU's climate policy objectives [10,18].

While the document is a national standard, because it follows ISO standards on smart city, sustainability and managing infrastructure (and therefore provides for international comparison) it will enhance Spain's ports competitive position internationally [10-12].

6.3. Implementation and Outlook.

Although there is still much to be done in terms of implementing the new Standard (UNE 178110:2024), some Spanish ports have already started to adapt their own transformation strategies to the ideas it sets out. Specifically, they are introducing "digital platforms", "monitoring systems for environmental issues" and also "frameworks for collaborative governance"[10],[13]. From what can currently be observed, those ports that operate under well defined legal frameworks show better cohesion between their "smart port" initiatives and how they relate to the wider urban area[10], [13].

However, the difficulties in implementing these concepts will likely be similar to all major changes - i.e., financial investment; organizational adaptation; staff training; and the need to establish a level of institutional maturity. But this should also represent an opportunity to achieve higher levels of operational efficiency; transparency; and sustainability. Strategically, the Standard represents a model for transforming existing port structures into "smart ports" which could fit well into larger digital territories[10].

7. Smart Port–City Integration and Future Prospects.

Port and city relationships have always had tension between them. Over the years, there has been urban expansion and port development occurring simultaneously however almost never moving in the same direction. Issues such as land use, transportation issues, environmental impacts and public acceptability for port operations have been ongoing. What has changed recently is not necessarily the underlying conflicts or the issue itself, it's how these issues will be addressed (and when) due to the digital transformation toward sustainability that is causing a reevaluation of the relationship between port and city [13,15].

Smart City is an overarching idea that provides both the theoretical and practical tools to address this; Smart Ports can be thought of as smart nodes rather than independent infrastructure located in larger smart city/territory systems. Functional, digital and strategic integration between port and city thus becomes, in this context, a decisive factor in generating economic, social and environmental value [13,15]. Smart cities manage mobility, energy, the environment and public services using data and interoperable platforms; ports, for their part, generate vast amounts of information on maritime and land traffic, goods flows, energy consumption and emissions that can be of enormous value for urban planning [11,12,15].

The integration of port systems with smart city platforms opens up concrete possibilities. Optimisation of urban and metropolitan mobility through the coordination of lorries, trains and ships. Reduction of environmental impacts through joint management of emissions and air quality. Improvement of spatial planning and land use. Increased transparency in decision-making. Viewed in this light, the port can function as a territorial intelligence hub with a real capacity to contribute to the objectives of sustainability and urban resilience [13,14].

For this integration to materialise, shared digital platforms are essential. However, their capabilities should not be overstated. On their own, they do not solve governance problems. Their operation requires multi-level models involving port authorities, local administrations, private operators and other stakeholders. The literature agrees on a clear diagnosis: the lack of clear governance frameworks remains one of the main barriers to effective integration between ports and smart cities [10,13]. Regulatory frameworks such as UNE 178110:2024 provide a useful foundation. They do not replace political decision-making or institutional cooperation, but they provide principles and structures that facilitate technical interoperability and organisational coordination [10,13].

From an environmental perspective, interoperability between port and urban systems enables more effective mitigation measures: smart access management, fleet electrification, optimisation of port calls, and shared emissions monitoring. On the social side of things, increased transparency and public access to information can foster better relationships between the port and citizens as well as improve the social legitimacy of port operations [13,15] . As stated by the OECD (2019), integration of logistics infrastructure into smart city strategies is a major element in enhancing both sustainable and cohesive territorial developments [13,15].

Several trends will likely be evident in the future, according to literature and policy makers. These include an increasing number of applications using AI and cognitive automation to make decisions regarding complex situations or to carry out adaptive management. Digital twin systems will continue to integrate into one another. There will be an emphasis placed upon strengthening cyber security and digital resilience within the context of high risk and very connected critical infrastructures. Data driven governance will become more prevalent among government agencies and other stakeholders in public and private sectors. Finally, there will be greater focus toward aligning with international climate and energy commitments which relate to carbon reduction targets [14,16].

However, these remaining challenges are predictably obvious: namely; the need for internationally harmonized regulatory frameworks, data protection, cyber security issues, and social implications due to the implementation of automation and digitalization [5,13,15].

From an academic point of view, researchers who have been conducting studies on smart ports have identified three main avenues of research as being particularly promising: comparative studies concerning the experience of smart ports; empirical measurements examining whether the increase in urban sustainability associated with intelligent operation of ports is truly realized; and the study of governance models based on open data and collaborative efforts between institutions [13,15].

In general terms, this analysis clearly demonstrates that if a comprehensive vision exists around automation of port activities supported by strong regulatory frameworks then what was once viewed as simply an operational improvement to port operations can evolve into a strategic tool for urban and regional development. Therefore, the convergence between smart ports and smart cities is not only possible; it is becoming a required answer to address many of the logistical, environmental and social challenges of the 21st century [10,13,15].

Conclusions.

Smart port design has evolved from focusing on automation and operational efficiency to a systemic model that integrates data, is interoperable and provides real time decision making. As such, the concept of a smart port represents a structural transformation where information becomes the strategic asset for the port system.

Port digitalization can only reach its full potential when it includes collaborative governance models and sustainability strategies, therefore showing how the architectural components (digital architecture), institutional management elements (governance) and environmental/social goals are all intertwined.

In this context, the standard for smart ports, UNE 178110:-2024, becomes relevant to structure this transition and provide a common framework for alignment between ports and cities in areas such as interoperability, data management and institutional coordination.

However, while port-city integration offers significant opportunities for economic value creation, environmental benefits and social improvements, several challenges remain (technological, organizational and regulatory) which require integrated approaches and greater institutional maturity to embed the smart port model into sustainable territorial development.

Smart port design has evolved from mechanization and operational efficiency to an integrated system that includes data integration and real-time decision making. Smart port design is therefore not just about becoming more automated but about structural transformation where information will become the primary strategic asset of the port system.

Port digitalization will only reach its full potential when it is developed alongside collaborative governance models and sustainability strategy. This underscores how digital architecture, institutional management elements (governance) and environmental/ social objectives are all interdependent.

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