Port planning in the face of artificial intelligence: towards an innovative methodological approach

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ABSTRACT

This paper explores the transformative role of Artificial Intelligence (AI) in port planning, focusing on its integration with Digital Twin technologies to enhance decision-making processes. From the perspective of a Port Authority, the study highlights AI's capacity to improve data integration, harmonization, and predictive analytics, addressing challenges related to the heterogeneity of datasets across institutional and territorial contexts. AI enables the transition from fragmented data to a coherent, standardized knowledge framework, facilitating scenario analysis and strategic planning, which are essential for effective port governance. AI supports infrastructure investments, operational resilience, and sustainable development by optimizing connectivity, forecasting cargo flows, and improving intermodal logistics. Additionally, AI enhances simulations for long-term resilience planning, particularly in response to climate change and evolving trade dynamics. The paper also examines AI's role in aligning port planning with European-level platforms such as TEN-TEC, the Ocean Digital Twin, and the ESPON program. These frameworks provide essential tools for evidence-based policymaking and territorial cohesion, reinforcing the integration of AI-driven spatial analysis into strategic port planning. By leveraging AI, Port Authorities can transition from reactive governance to proactive, data-driven decision-making, ensuring efficiency, competitiveness, and resilience in modern port management.

Keywords: Port Governance, Port Planning, Artificial Intelligence (AI), Digital Twins.

1. Introduction

This paper builds upon the conclusions presented at the MARLOG 2024 conference, where the transformative potential of a decoupled architecture for seaport digital twins was explored [1]. The 2024 study underscored the critical role of real-time data integration between physical and digital twins, highlighting enabling technologies such as artificial intelligence (AI), augmented reality, virtual simulations, big data analytics, and the Internet of Things (IoT). Central to this approach was the synergistic interplay of the "digital twin - artificial intelligence - IoT" triptych, where IoT devices detect real-world events, digital twins dynamically represent these events, and AI processes and analyzes the data to support predictive decision-making. By leveraging these technologies, the decoupled architecture was identified as a foundational solution for implementing dynamic, data-driven representations of seaports [2].

In particular, the 2024 paper anticipated that, from the perspective of a Port Authority, the digital twin serves as a strategic tool to support port planning [1]. By enabling the simulation of various scenarios for infrastructure development, digital twins provide a powerful means to optimize resource allocation and decision-making processes. Through its dynamic and data-driven capabilities, the digital twin allows Port Authorities to assess the potential impacts of new developments, expansions, or operational changes in a virtual environment before their physical implementation. This approach ensures that planning decisions are informed by comprehensive insights, aligning with both operational efficiency and sustainability objectives [3].

In this perspective, the development of the new “Port System Master Plan” (i.e., “Piano Regolatore Portuale di Sistema”) for the North Tyrrhenian Sea Port Authority (AdSP-MTS) represents a groundbreaking opportunity. This initiative aims to redefine the planning and management of port infrastructures by integrating advanced technologies such as Digital Twins, Artificial Intelligence (AI), and Geographic Information Systems (GIS). These innovations are expected to enhance operational efficiency, sustainability, and strategic coordination across the port network, including Livorno, Piombino, and the islands of the Tuscan Archipelago.

This paper is structured into three interconnected sections, each addressing critical aspects of port planning and governance in the context of artificial intelligence (AI) and digital twin technologies from the perspective of a Port Authority.

The first section explores the transformative impacts of AI and digital twin technology on port system governance. It examines how the integration of these tools redefines operational paradigms, enabling more efficient and data-driven management practices. Focusing on the North Tyrrhenian Sea Port Authority (AdSP-MTS) as a case study, it highlights the strategic choices, investments, and innovation initiatives already implemented or planned to enhance port operations and governance.

The second section delves into the specific ways AI supports Port Authorities in improving data integration, standardization, and quality. It emphasizes AI's pivotal role in harmonizing heterogeneous datasets and creating a robust "knowledge framework" that underpins effective port planning. By transforming fragmented information into actionable insights, AI enables decision-makers to navigate the complexities of modern port management with greater precision and foresight.

The third section builds upon these foundations, illustrating how AI serves as a catalyst for innovative and strategic port planning. It analyzes how AI-driven tools, such as predictive analytics and simulations, empower Port Authorities to optimize infrastructure investments, adapt to shifting market demands, and enhance operational resilience. This section also examines the role of AI in fostering integration with European-level digital twin platforms, ensuring alignment with broader regional and global objectives.

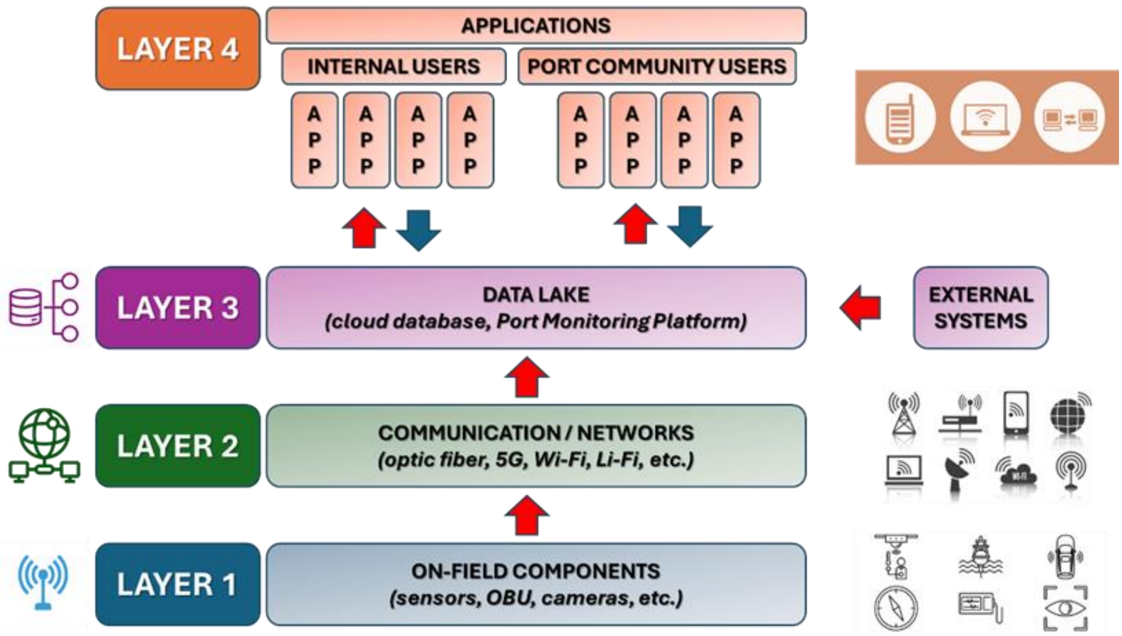
By addressing these themes, the paper provides a comprehensive overview of how AI and digital twins are reshaping port governance and planning.

2. Artificial Intelligence and Digital Twins: Governance Impacts and Innovations by the North Tyrrhenian Sea Port Authority

Without prejudice to the fact that Artificial Intelligence, in the decoupled architecture chosen by AdSP-MTS, is connected to the solutions/applications layer, it should first of all be highlighted that the real-time data flow between physical and digital twins requires the use of different technologies enablers, such as artificial intelligence, augmented reality, virtual simulations, big data & analytics and the Internet of Things (IoT) [4]. In particular, the importance of the "digital twin - artificial intelligence

- IoT" triptych emerges: the IoT detects an "event" through a device, after which object, event and device are represented on the digital model of the port; therefore the application of AI allows the information received to be correctly processed and analyzed, integrating it with others, especially in predictive terms [5].
AI is deeply connected to digital twin technology, enabling advanced functionalities that enhance their effectiveness. By analyzing data from sensors, IoT devices, and other sources, AI extracts insights, identifies patterns, and informs decision-making. It also facilitates predictive analytics, enabling digital twins to anticipate problems, failures, or performance fluctuations and support proactive maintenance [6]. Machine learning refines models and simulations, making digital twins more accurate and realistic, while autonomous decision-making allows them to act based on real-time data and predefined rules, crucial in complex environments like ports. AI improves adaptive control systems by dynamically adjusting parameters to maintain optimal performance [7]. Natural language processing (NLP) further enhances usability, enabling intuitive interactions with digital twins through natural language queries. Additionally, AI excels at recognizing patterns, identifying inefficiencies, anomalies, and trends, which informs system optimization. Dynamic simulations powered by AI allow digital twins to assess scenarios and outcomes, aiding strategic planning and risk management. These capabilities make AI-integrated digital twins essential for optimizing operations and addressing challenges in dynamic environments.

The next section details the strategic, technical, and administrative reasons that led to the adoption of this "decoupled" approach. Below, actions and projects related to AI, the Digital Twin, and enabling technologies — completed, underway, and planned by the Northern Tyrrhenian Sea Port System Authority (AdSP MTS) — are listed and grouped by reference layer.



Layer 1 – "On-field-components"
Between 2025 and 2027, AdSP MTS aims to implement the Sensorization and Port Monitoring Platform Development Plan for the ports under its jurisdiction. This initiative will utilize advanced technologies and instrumental solutions to drive innovation in port and peri-port operations. The existing sensor network, developed through European projects and targeted investments, provides a robust technological platform for monitoring environmental, acoustic, climatic, meteomarine, and road conditions, supporting both real-time management and predictive planning.
The integration of state-of-the-art sensors and AI tools is pivotal for enhancing data collection and analysis, enabling precise predictive models and innovative digital applications.

i. Since 2018, a sensor network has been established in Livorno, Piombino, and Portoferraio for monitoring environmental (air quality), acoustic (sound level), marine weather (wave height, currents, anemometers), and bathymetric conditions (multi-beam bathymeters). During 2024-2025, additional instrumentation will be installed to monitor all physical specifications critical to understanding port operations, including a prototype in a small local area to refine and scale the tested solutions.
ii. In 2024, all light towers and pilings in the Port of Livorno will be sensorized for remote light point management and monitoring of lighting fixture functionality.
iii. Between 2018 and 2021, a network of next-generation photonic radars for detecting small boats without AIS signals or antennas was developed and will undergo further testing in 2024.
iv. During 2021-2022, augmented reality tests were conducted using smart glasses, and additional functionalities to support port controls are planned for 2024.
v. Within the 2024-2025 SAFARI project, in collaboration with international partners (e.g., University of Lille, University of Strathclyde, Port of Lisbon), a sensor network will be deployed to monitor port infrastructure and evaluate its resilience.
vi. In the 2023-2024 period, within the URSA MAJOR NEO and MERIDIAN projects, EU-funded CEF initiatives will pilot digital solutions for road traffic management along the Florence-Pisa-Livorno corridor, including applications for hauliers.

Layer 2 – "Networks and Connectivity"

i. Between 2020-2022, 5G network tests were conducted to optimize operational flows at a bulk terminal, coupled with an evaluation of environmental benefits from process optimization.
ii. In 2024, under the 5GMASS project (ESA-funded), 5G antennas, high-definition cameras, and software solutions will be installed to remotely test the maneuvering of commercial ships [8].
iii. Li-Fi technology trials will be conducted in 2024, with innovative systems for data transfer via sensorized LED lights.
iv. The 2025-2027 Three-Year Program includes the installation of 5G antennas to enhance network connectivity for integrated port monitoring.

Layer 3 – "Convergence Platform – Data Lake"

Between 2024 and 2026, AdSP MTS plans to re-engineer the MONICA platform, creating the M.IA (Monitoring Innovative Architecture) system. This open, modular platform will integrate the existing data lake and certified data sources, enabling third-party development for vertical applications. M.IA will seamlessly connect with digital twin and AI systems to support advanced port community services.

Layer 4 – "Applications"

i. MONICA Platform Applications: Solutions for monitoring environmental activities, naval movements, emissions, noise levels, passenger support, and emergencies will be maintained and enhanced.
ii. C-ITS Platform: The URSA MAJOR NEO project developed a peri-port sensor network for services like smart parking for hauliers.
iii. Digital Twin for Sustainable: The CEF-funded VERKKO project (2024-2026) will develop a digital twin to optimize road traffic emissions related to port activities.
iv. Emission Monitoring Digital Twin: Between 2024-2026, ESA-funded AI applications will monitor and predict port-city environmental emissions using satellite data and traffic models.
v. AI for Pollutant Monitoring: AI will quantify pollutants along logistics chains using MONICA and TPCS data, supporting emissions reduction strategies.
vi. AI-Powered Chatbot: A chatbot (2024-2026) will disseminate institutional analyses and offer specialized topic-specific support.
vii. Port Berth Management Algorithm: In 2024, an algorithm will optimize berth assignments using emission, acoustic, and procedural data.

viii. Energy Optimization for Light Towers: Between 2024-2025, AI applications will reduce energy consumption and environmental impact of sensorized light towers.
ix. AI and BIM Integration: Between 2023-2024, AI will be integrated with BIM software for advanced maintenance planning.
x. AI for Image Processing: Between 2024-2025, AI will process images from thermal cameras, underwater scanners, and other devices for infrastructure monitoring and hazard detection.

3. The Role of AI in Improving Data Integration and Quality for Port Planning

Building on this foundation, the section analyzes how artificial intelligence can specifically support Port Authorities in port planning, particularly in terms of comparability, standardization, and processing of data sets and information (i.e., the "knowledge framework") available to planning decision-makers.

In general, first of all AI can streamline the processing of complex and diverse data sources, transforming fragmented and heterogeneous information into a cohesive and standardized framework. From this data-driven point of view, the following observations can be made regarding the information upstream process, which provides essential data needed for effective port planning:

1. At the first level, data is directly acquired from the "digital twin," which is based on real-time observation of the port environment. However, this raw data often contains gaps, inconsistencies, or noise due to sensor limitations or environmental factors. Artificial intelligence enhances this dataset by integrating information from multiple sources, correcting errors, and filling gaps to create a more accurate and reliable representation of port operations. “Soft sensing” exemplifies how artificial intelligence can enhance datasets acquired directly from the digital twin. By combining data from a network of low-cost physical sensors with advanced machine learning models, soft sensing addresses gaps, inconsistencies, and noise often present in raw sensor data. For instance, in monitoring particulate matter generated by port activities, such as dry bulk handling, low-cost sensors dispersed throughout the port environment provide extensive raw data coverage. AI then refines this input by calibrating it against data from high-precision sensors strategically placed in key locations. This process fills informational voids and ensures a consistent and accurate representation of port operations within the digital twin. Soft sensing thus transforms raw data into actionable insights, enabling more precise real-time monitoring, predictive analysis, and prescriptive decision-making, all of which enhance the operational and strategic capabilities of the Port Authority.

   Furthermore AI algorithms can also standardize data formats, ensuring consistency across diverse systems. Artificial intelligence (AI) plays a pivotal role in enhancing the digital twin, particularly when it relies on data acquired from on-field components, such as sensors deployed by the Port Authority and those operated by external public or private entities (e.g., weather stations, environmental sensors, air quality monitors). From the perspective of a Port Authority, the main challenge lies in the heterogeneity of these sensor-based data sources, which often differ in format, resolution, and quality, complicating their integration into a unified monitoring framework [9].

   AI addresses these challenges by standardizing, normalizing, and enhancing sensor data streams. Machine learning algorithms can identify inconsistencies, correct errors, and fill data gaps, ensuring that the information fed into the digital twin is accurate, reliable, and complete. For example, AI can reconcile data from different sensors or infer missing measurements, allowing the digital twin to maintain a coherent and high-resolution representation of the port's physical environment.

   Furthermore, while the ultimate objective is the development of a comprehensive data lake supported by standardized APIs, the current absence of such an infrastructure amplifies the importance of AI. AI can act as a bridge, transforming raw sensor data from diverse sources into compatible formats and making it immediately usable within systems like MONICA. This enables the Port Authority to integrate and utilize a wider range of information, enhancing the monitoring and management capabilities of the digital twin.

This approach ensures that the Port Authority remains at the forefront of port governance, leveraging sensor-based monitoring systems to make informed, real-time decisions that improve operational efficiency, sustainability, and resilience [10]. This exemplifies how, for a Port Authority, the digital twin should be regarded as an "Advanced Port Monitoring System" enhanced by AI. By integrating real-time data from on-field components and external sources, and leveraging AI to process, harmonize, and enrich this information, the digital twin transcends traditional monitoring. It becomes a dynamic tool that not only observes but also interprets and predicts, enabling the Port Authority to optimize governance, planning, and operational efficiency [11].

2. There are also data required by law, relating to existing conditions, plans, and programs at the European, national, regional, and local levels. In Europe, the planning process is meticulously regulated not only in terms of the stakeholders to be involved and their methods of involvement but also regarding the information and knowledge frameworks on which it must be based. Referring specifically to the Italian regulatory framework (similar in many respects to other European experiences), port planning relies on data not limited to the port as a confined area (i.e., the port area and the so-called "customs circuit") but also encompassing the city-port interface and broader infrastructures and assets, particularly road networks, rail connections, and intermodal logistics facilities. Examples include Municipal Urban Plans (PRG), Regional Territorial and Transport Plans, the National General Transport and Logistics Plan, Three-Year Public Works Programs, Environmental Impact Assessments (VIA), and agreements with public or private entities.
   Such data is dispersed across numerous platforms, digital archives, and repositories managed by administrations and institutions other than the Port Authority, which remains responsible for port planning. These datasets are often complex and structured using varying standards, architectures, and formats (whether geolocated or not) [12].
   From this perspective, AI can be a valuable tool for integrating, harmonizing, and enhancing data from diverse sources, thereby supporting the Port Authority in strategic planning. By employing machine learning algorithms and advanced processing techniques, AI can standardize formats, normalize information, and identify gaps in datasets, ensuring consistency and completeness across different systems. Additionally, AI enables the extraction of meaningful insights from large volumes of data, enhancing the understanding of connections between the port, the city, and logistical infrastructures.
   AI can also geolocate and aggregate dispersed data, making it more accessible and usable for decision-makers. This is essential for building a comprehensive knowledge framework that includes critical information on road and rail networks, intermodal facilities, and urban and infrastructure development plans. In doing so, AI supports the creation of an integrated informational ecosystem that facilitates data-driven decision-making, improving the quality and effectiveness of port planning.

Port Authorities, AI and European-level platforms. AI plays a pivotal role in enabling integration with European-level "digital twin" platforms by addressing key challenges associated with the heterogeneity of data sources managed by various institutional stakeholders. For a Port Authority, the ability to align its systems with broader European platforms is essential to achieving effective and informed port planning. A Port Authority must consider not only local operational needs but also how its infrastructure and logistics interact with regional, national, and transnational systems. This ensures that port planning supports economic growth, sustainability, and compliance with regulatory frameworks. AI, by harmonizing and standardizing data, equips Port Authorities with the tools necessary to contribute to and benefit from European-level initiatives.
Port operations generate vast amounts of data from environmental sensors, logistical systems, and urban interfaces, which often differ in structure, format, and granularity. Through advanced machine learning algorithms, AI can harmonize and normalize these disparate datasets, ensuring compatibility with external systems. Moreover, AI adds value by enriching local datasets with predictive and

prescriptive analytics, enhancing decision-making processes. For a Port Authority, this integration supports the creation of a comprehensive knowledge framework, fostering better coordination between local initiatives and European strategic objectives.
A key example of this integration is the TEN-TEC platform (Trans-European Transport Network - Technical Assistance and Information Exchange), managed by the European Commission. This platform supports the development and monitoring of the TEN-T network, which aims to ensure efficient and sustainable transport infrastructure across Europe. By leveraging AI to refine and harmonize data on port infrastructure, logistical flows, and intermodal connectivity, Port Authorities can supply valuable input to TEN-TEC. In return, they gain access to insights on trans-European transport corridors, enabling alignment of local planning with regional and European strategies. This ensures that ports are not only compliant with overarching goals but also positioned as critical nodes in the broader transport network.
Another significant initiative is the Ocean Digital Twin, developed under the European Mission "Restore Our Ocean and Waters by 2030." This platform monitors, simulates, and manages the health and resilience of Europe's marine environments. AI enables Port Authorities to contribute real-time and predictive data on emissions, marine traffic, and environmental impacts, enriching the platform's modeling capabilities. In exchange, the Ocean Digital Twin provides actionable insights into ocean health and climate resilience. For example, it helps ports mitigate the environmental impact of maritime operations and supports the planning of sustainable infrastructure, aligning local efforts with global sustainability targets [6].

For a Port Authority, these integrations are not merely technical advancements but fundamental tools for achieving comprehensive and forward-looking port planning. By contributing to European platforms, ports strengthen their ability to anticipate future challenges, optimize operational efficiency, and enhance their environmental sustainability. AI ensures that local data becomes part of a larger informational ecosystem, enabling Port Authorities to play an active role in shaping transnational governance frameworks.
In conclusion, the integration of AI with European digital twin platforms empowers Port Authorities to achieve better planning outcomes by bridging local and international perspectives. This alignment ensures that port planning is not only efficient and sustainable but also strategically coherent with broader regional and global objectives. By fostering such integrations, AI not only strengthens the role of Port Authorities as local enablers of digital transformation but also positions them as key contributors to collaborative European governance frameworks.
In conclusion, it is worth highlighting that the actions and projects of the AdSP-MTS mentioned above are largely carried out within the framework of European calls. In this context, it should be noted that, following the "project pipeline" logic—depending on the varying technological and market maturity of the initiatives (proof of concept, prototype, pilot, demonstrator, industrialization)—the AdSP-MTS has leveraged various European programs, such as H2020, Interreg, LIFE, and CEF. The participation in multiple European programs supporting innovation in the ICT field and ecological transition should not be seen solely as a source of financial support for "frontier" actions but also as an opportunity to build strategic partnerships with leading industrial entities, technology providers, other ports/interports and corridor infrastructure managers, universities, and research institutions at both European and international levels. For this reason, the AdSP-MTS has established a dedicated internal organizational unit, the "Development, European Programs and Innovation" Directorate, which ensures alignment between its innovation initiatives and European projects.
In this regard, it is worth noting that the European ESPON program can support Port Authorities, including through cooperation among them, in supporting evidence-based policy-making and territorial planning. By leveraging ESPON's research and tools, Port Authorities like the AdSP-MTS can integrate spatial analyses into their strategic frameworks, enhancing their capacity to address challenges such as accessibility, sustainability, and climate resilience. ESPON's focus on territorial cohesion and the dynamics of European transport and logistics networks provides valuable insights for aligning local port planning with broader regional and EU-level objectives. This integration reinforces the commitment to developing data-driven and strategically coordinated approaches. In particular,

Artificial Intelligence (AI) can play a key role in ESPON's objectives by enabling advanced data analysis, predictive modeling, and scenario simulations. These capabilities enhance the interpretation of complex territorial data, allowing for more precise insights into transport, logistics, and environmental challenges. By integrating AI-driven tools, ESPON can further empower Port Authorities to develop innovative, data-driven strategies aligned with regional and European priorities.

4. Artificial Intelligence as a Catalyst for Port Planning

Datasets used in different institutional contexts—both within the European Union and in neighboring countries—are often highly heterogeneous. This heterogeneity arises from variations in planning levels (national, regional, local), the diverse nature of stakeholders (public, private, or mixed), and the varied roles assigned to Port Authorities, such as regulatory oversight, commercial development, infrastructure management, service delivery, and port operations. Artificial intelligence offers powerful tools, including predictive analytics and machine learning algorithms, to address these challenges. By integrating and harmonizing disparate datasets, AI enhances the consistency and reliability of the knowledge framework, enabling comprehensive scenario analysis and facilitating comparisons across territorial and institutional contexts. This, in turn, empowers Port Authorities to navigate fragmented planning systems and complex governance structures with more informed and strategic decision-making.

The findings from the paper presented in 2024 in MARLOG 13 highlighted the potential of digital twin technology to drive innovative port governance, emphasizing key capabilities such as predictive infrastructure maintenance, monitoring and control, security, and operational optimization of port equipment [1]. These functions demonstrated the transformative role of digital twins as dynamic tools for addressing the complex challenges of port management. Building on these insights, and considering AI's ability to harmonize and enhance heterogeneous data sources, it becomes clear how AI can further support port planning. Initially, AI plays a crucial role in creating a coherent, high-quality, and comparable knowledge framework (the "upstream" of information). Once this foundation is established, AI enables advanced data analysis and processing (the "downstream" of information).
AI can support port planning—understood here in its broadest sense as the decision-making processes that guide strategic positioning, development policies, and investment strategies. This includes determining port functions (e.g., cargo or passenger operations, and specific types of cargo such as containers, Ro-Ro, bulk, project cargo, or new vehicles), identifying necessary infrastructure investments, and evaluating potential alternative uses of port infrastructure (e.g., port layout decisions). AI empowers these processes by providing robust data-driven insights, facilitating more effective and forward-looking decision-making. In particular, from the perspective of a seaport, AI can significantly support port planning in various ways, which can be categorized into four key aspects:

4.1. Strategic Positioning and Framework Development

From the perspective of a Port Authority, AI offers transformative potential in defining the strategic positioning of the port [13]. By analyzing global and regional trade trends, market dynamics, and shifts in trade routes, Port Authorities can align their development strategies with emerging economic opportunities. For example, predictive models can assess the growing demand for renewable energy logistics or the impact of new market entrants on container flows. By integrating these insights into advanced business intelligence systems, Port Authorities enhance their capacity to make informed decisions that strengthen their competitiveness and resilience.
AI also enables detailed evaluations of the economic impacts of infrastructure projects, such as new terminals or intermodal hubs, which are critical for a Port Authority's resource allocation. Forecasting revenue streams, job creation, and regional benefits ensures that investments deliver the highest value. When integrated into business intelligence frameworks, these analyses help Port Authorities monitor and adapt their strategies in real time, promoting sustainable and efficient growth.

Moreover, AI supports the optimization of connectivity between port operations and the hinterland, a key concern for any Port Authority. By analyzing cargo flows, traffic patterns, and industrial synergies, it identifies opportunities to enhance intermodal efficiency. For example, evaluating the potential of logistics parks or rail terminals enables better alignment with regional economic objectives. Through business intelligence tools, these insights can be visualized and shared among stakeholders, fostering collaboration and reducing inefficiencies across the supply chain [14].

4.2. Infrastructure Investment and Functional Allocation

For a Port Authority, long-term infrastructure planning is fundamental to achieving both operational efficiency and strategic competitiveness. AI evaluates these needs by analyzing trends in cargo volumes, vessel sizes, and operational requirements. For instance, it can predict future demands for container berths or assess the viability of investing in LNG bunkering facilities [15]. When these evaluations are integrated into business intelligence platforms, Port Authorities can prioritize investments that balance cost-effectiveness, environmental impact, and alignment with broader strategic goals.

AI also aids in the functional allocation of port areas, which is central to a Port Authority's governance responsibilities. By analyzing operational data and market trends, it provides insights into the optimal use of land, whether for container storage, bulk cargo handling, or renewable energy installations [16]. Combined with real-time updates from business intelligence systems, these recommendations ensure that land use decisions remain adaptive to changing conditions and support long-term efficiency.

In addition, AI-driven simulations allow Port Authorities to explore alternative uses for infrastructure. A terminal initially designed for Ro-Ro operations, for example, could be evaluated for conversion into a logistics hub or renewable energy facility. These simulations, supported by business intelligence, help decision-makers compare potential outcomes and optimize the value of port assets, ensuring flexibility and resilience in an evolving market.

4.3. Data Integration and Analysis

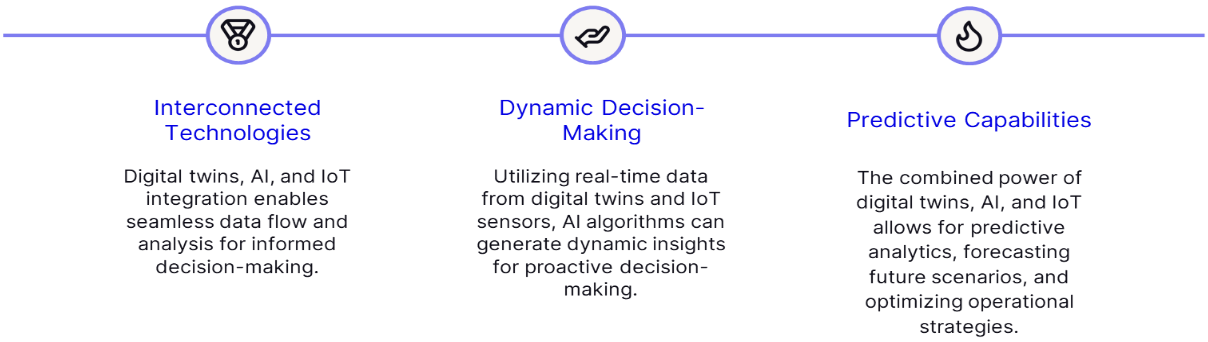
Port Authorities face significant challenges in integrating data from diverse sources, including logistics systems, environmental sensors, and urban interfaces. AI addresses these challenges by leveraging machine learning algorithms to identify patterns in large datasets and providing predictive insights into the outcomes of strategic decisions [17]. For instance, it can forecast how increased cargo flows might affect port capacity, enabling proactive adjustments to infrastructure or operations. Integrated into business intelligence dashboards, these insights become actionable, allowing Port Authorities to navigate complex scenarios with greater confidence.

Moreover, data visualization tools powered by AI enhance a Port Authority's ability to interpret and act on complex datasets. Dashboards displaying real-time emissions, cargo movements, and infrastructure utilization provide a comprehensive overview of port operations. Business intelligence platforms further enrich these capabilities by integrating multiple data sources, enabling Port Authorities to align their decisions with sustainability goals and ensure efficient resource allocation.

4.4. Simulations and Resilience Planning

Simulations are an essential tool for Port Authorities in both operational and strategic planning. AI enables sophisticated models to evaluate the effects of introducing new technologies, such as automated cranes, or the impacts of policy changes, such as new trade agreements. These simulations, contextualized with historical and real-time data through business intelligence platforms, empower Port Authorities to make robust and dynamic decisions.

Resilience planning is another critical area where AI supports Port Authorities. By modeling the impacts of climate change, such as sea-level rise and extreme weather events, AI helps guide the design of resilient infrastructure. For example, it can simulate storm surge scenarios to inform the development of breakwaters or flood defenses. Business intelligence tools consolidate these simulations with other planning data, providing Port Authorities with comprehensive strategies to ensure both sustainability and long-term viability [18].



5. CONCLUSIONS

In conclusion, the integration of Artificial Intelligence (AI) and Digital Twin technologies represents a transformative step forward for port planning and governance. From the perspective of a Port Authority, these innovations not only enhance operational efficiency and sustainability but also redefine the strategic approach to managing complex maritime environments. By leveraging AI to harmonize heterogeneous data sources and simulate predictive scenarios, Digital Twins enable a dynamic, data-driven framework that supports more informed and effective decision-making.
The North Tyrrhenian Sea Port Authority (AdSP-MTS) exemplifies how targeted investments in enabling technologies—such as IoT, big data analytics, and augmented reality—can drive innovation and competitiveness within the port system. The layered approach adopted by AdSP-MTS, spanning on-field components, networks, convergence platforms, and advanced applications, demonstrates the potential of integrating cutting-edge solutions to optimize resource allocation, monitor environmental impacts, and align with broader European and global objectives.
Furthermore, the alignment with European platforms such as TEN-TEC and the Ocean Digital Twin underscores the importance of collaboration and standardization at regional and international levels. AI not only facilitates this integration but also positions Port Authorities as key players in achieving sustainability, resilience, and economic growth within the broader transport and logistics network.
Ultimately, the combination of AI and Digital Twin technologies provides a methodological foundation for addressing the multifaceted challenges of modern port management. As demonstrated in this paper, these tools empower Port Authorities to transition from reactive governance to proactive planning, ensuring that seaports remain vital, adaptive, and sustainable hubs in an increasingly interconnected world.

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