DIGITal Twins applications for safer and greener Adriatic PORTS operations

Common Strategic Position Paper on how to Improve Digital Twin applications in Adriatics ports

(D.1.3.1)

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1. Executive Summary

1.1   Objective

DIGITPORTS focuses on the application of Digital Twins (DT) to Adriatic port ecosystems and how DT and Artificial Intelligence (AI) applications will help in switching to data-led decision-making processes:

1) to plan and develop sustainable business strategies for land and seaport operations and real estate valorization (e.g. ship arrival and departing scheduling tool);

2) to reduce costs for maintenance of real estate port buildings and quays, based on predictive maintenance schemes (e.g. use of sensors and drones for monitoring purposes);

3) to use DT to support the territorial management, about managing concessions fees, bathymetries and predictive maintenance and dredging, Port Reservation System for more efficient berthing allocation, better gates management, just to name a few.

The pilot DT tools developed in DIGITPORTS Consortium must be capable of integrating big amounts of data within complex contexts and the evolution of a web-based GIS (Geographical Information System) that encompasses both administrative, economic, environmental, structural and operational model replica of the real port.

The objective of this document is to establish a unified strategic framework for implementing Digital Twin (DT) technology across Adriatic ports, enhancing their digitalization, operational efficiency, and sustainability. By integrating insights into benchmarking analyses, training, and pilot projects, the document provides actionable recommendations to address operational inefficiencies, foster cross-border collaboration, and enable data-driven decision-making. It serves as a blueprint to guide port authorities in adopting scalable, interoperable, and sustainable digital solutions, aligning with global best practices and regional development goals.

1.2   Background scenario and key Insights

Adriatic Ports have experienced a wave of digitalization and automation initiatives between 2019 and 2024, to adapt to the pressure on efficiency caused by competition, the post-pandemic effects on global supply chains resilience and cost structures, the scale expansion of container shipping and logistics, the higher accountability requisite of ports operations due to proximity of city centers and

negative externalities and, in general, a greater demand for transparency and objective measurements of pollutants, connected also to EU revision of public procurement schemes for concessions.

Italian and Croatian Port Authorities act as public body regulators of ports operations and strive for creating the baseline conditions for a safer, greener and more sustainable competitive port system.

However, the pace of digital transformation in the maritime industry is still slow due to industry specific characteristics, such as high asset costs, high development costs, aging workforce and strict regulations, negatively impacting the ability to digitize effectively. Also, due to the traditional set-up of the organizations, conventional players often lack the skills for successful digital adoption.

Common problems to be tackled are twofold: reducing operational costs and carbon footprint (both on containers, passengers and multipurpose terminals) with the use of less public resources.

DIGITPORTS aims to lead the full digital transition of Adriatic Ports through the adoption of a common strategy on applications of Digital Twin, creating a network of digital support – decision making tools, to be used at local and cross-border level.

DIGITPORTS will adopt a common strategy to assure a quality and scalability of the digital tools put in place, helping port authorities to achieve full digitalization of administrative procedures and planning, striving for decarbonization of transport and better use of resources; developing new digital tools for training and planning activities (different levels of entry points: creation of digital mapping, software model development, integration of existing databases and similar).

Benchmarking analyses conducted in the first phase of DIGITPORTS project reveal significant disparities in digital adoption, with fragmented systems, limited interoperability, and underdeveloped data governance frameworks hindering efficiency.

However, the potential benefits demonstrated and analyzed within the training sessions that followed highlight the transformative power of advanced technologies, such as IoT, AI, and predictive analytics, in achieving operational excellence and sustainability. Cybersecurity measures and data governance frameworks remain underdeveloped, exposing ports to risks in an increasingly digital ecosystem. Furthermore, alignment with sustainability goals, including carbon footprint reduction and energy efficiency, is inconsistent across the region.

These insights underscore the necessity for Adriatic ports to adopt a unified strategy, harmonizing their efforts to align with international standards while addressing specific regional challenges.

The DIGITPORTS project provides a structured approach to achieving this transformation. By leveraging insights from training sessions, and pilot projects, the ports can address skill gaps, improve cross-border collaboration, and streamline decision-making processes. Strategic alignment with sustainability objectives, such as reducing carbon footprints and integrating renewable energy, further ensures that the digitalization efforts contribute to long-term environmental goals. The document synthesizes these findings into actionable recommendations, setting a clear path for Adriatic ports to enhance their competitiveness, resilience, and ability to meet the demands of an evolving maritime sector.

1.3   Recommendations

The report underscores the need for a strategic, phased approach to digitalization.

Digital Twins (DT) are not new to some industries (automotive, manufacture and scientific research) but their applications in ports are innovative because most DT systems that are based on multiple levels of control and automation can generate data using embedded sensors and/or software.
Thanks to well-known technical drivers such as connectivity via wireless communication technologies, standards for devices, ubiquitous computing, ports' ecosystems can benefit too from trends as Industry 4.0 and the Industrial Internet of Things (IIoT).
Many applications in these areas are based on data collection and analysis, combined with artificial intelligence. These developments escalate the importance of the digital twin approach. Data from the actual physical system can be used to continuously synchronize the digital twin, ensuring that the real-time, virtual representation always reflects the current state of the real system.
At the beginning, ICT and training investments will be needed, but in the long run DIGITPORTS wants to prove that DT can help save time and public resources, for example by testing and running different hazardous scenarios without risking real incidents, or without having to interrupt operations to make real-time forecast and rescheduling of berthing requests, as well as better plan resources and energy consumption on port buildings by using predictive maintenance and sensors (just to name few of the endless possible DT applications).

The Cross-Border approach is crucial in addressing this common challenges because the Adriatic Sea must be conceived as one integral maritime space because annually about 7.000 ships with dangerous cargo (such as tankers oil, chem, gas and containers) sail in its waters and on top of that we can add up the commercial, the leisure and the local traffic. Against this scenario, the only

cooperation approach proven to be efficient to obtain sustainable growth of Blue Economy is the transnational one.

To achieve these goals, the ports, which are the crucial nodes in the global supply chain, needs to upgrade their assets and toolboxes so to become technology-facilitators of port ecosystems, with the objective of full digitalization of information and culture-change drivers of innovation. Indeed, Port Authorities, terminal operators, suppliers, and customers are becoming more closely aligned because of the processes and businesses becoming more and more digitally and globally connected, and Adriatic port authorities must play a pivotal role in this ever-changing playing field.

The maritime industry struggles with widespread digitalization efforts in comparison to other fields like the automotive industry or manufacturing because it already faces extraordinary complexity in its products and organizational structures, as well as rising delivery costs or public opinion's pressure for decarbonization. This is even more true in the context of the Adriatic Sea Basin where the congestion is posing serious challenges not only on the environmental footprint (and public health) but also in the port operations' performances, safety and security of the navigation and port operations and management, and, in turn, to the attractivity of the East-Med areas for reshoring and production sites.

Taken into consideration the above described peculiarities of DT applications on Adriatic Ports ecosystem, key recommendations can be summarized as follows:

- **Technology Implementation**: Initiate pilot projects for digital twins, IoT devices, and AI-powered analytics in operational areas like cargo handling (operated by private companies on a concessions scheme) and assets and resource management.
- **Regional Cooperation**: Establish cross-border data-sharing frameworks and foster collaborative projects to leverage shared resources and knowledge.
- **Capacity Building**: Conduct comprehensive staff training programs to bridge skill gaps and enhance technological readiness.
- **Clear vision and organizational culture change:** clearly state advantages of a DT modelling adoption so that all stakeholders (internal and external) can trust the process, which requires sharing, transparency, trust and accountability and commit to an unprecedented organizational change driver.
- **Policy Reforms**: Develop a unified digitalization strategy aligned with EU directives, streamline regulatory processes, and strengthen cybersecurity policies.

- **Sustainability Alignment**: Invest in renewable energy infrastructure and green technologies to reduce environmental impact and meet EU Green Deal objectives.
- **Funding and Investments**: Explore public-private partnerships and optimize access to EU funding mechanisms to address financial gaps.

By adopting these recommendations, Adriatic ports can address their current challenges, capitalize on their strategic geographical position, and emerge as competitive, sustainable hubs in the global maritime network.

2. Introduction

2.1 Background and Context

Adriatic ports play a critical role in regional and international trade, serving as key nodes in the European maritime network. In recent years, these ports have faced mounting challenges, including pressure to enhance operational efficiency, adapt to evolving global supply chains, meet sustainability goals, and address regulatory demands. Digitalization and automation have emerged as crucial solutions to address these challenges, offering the potential to improve port operations, reduce environmental impacts, and optimize resource utilization.

Despite progress, the pace of digital transformation in the Adriatic maritime sector has been slower than desired, hindered by factors such as high costs, an aging workforce, and the complexity of adapting legacy systems. This situation underscores the importance of a coordinated approach to digitalization, leveraging best practices and fostering cross-border cooperation to maximize efficiency and sustainability.

The DIGITPORTS project, funded under the Interreg VI-A Italy-Croatia programme, aims to address these challenges by introducing innovative digital twin applications to the Adriatic port ecosystem. This initiative is expected to enhance the digitalization, sustainability, and operational efficiency of these ports, enabling them to transition into modern, data-driven, and environmentally sustainable hubs.

2.2 Summary of the DIGITPORTS Project

DIGITPORTS aims to help solve a specific challenge in the maritime transport, i.e. how to exploit the technical opportunities of Digital Twins to upgrade the digitalization level of port authorities, public services of general interests and how to integrate better planning solutions at cross-border level.

The full digitalization of ports will leverage the Blue Economy growth of the Adriatic territories and beyond, being the port's authorities engine for growth in terms of works, services and global supply chain nodes connecting manufaturers and consumers of Southern Europe to ther rest of world.

DIGITPORTS partnership is geographily covering all the Adriatic Sea, and the Authorities have all technical and management capacities to carry out the pilot activities so to phisically produce the change at cross-border level, bringing together Core and Comprehensive European sea ports in the Adriatic area of Italy and Croatia:

Code	Organization	Acronym
LP1	North Adriatic Sea Port Authority (ports of Venice and Chioggia) - Lead Partner	NASPA
P02	Port Network Authority of the Eastern Adriatic Sea (ports of Trieste and Monfalcone)	PNAEAS
P03	Port of Ravenna Authority	ADSPMACS
P04	Port of Rijeka Authority	PRA
P05	Port of Ploče Authority	PPA
P06	Port of Zadar Authority	ZPA
P07	Port of Split Authority	SPA

In addition, Central Adriatic Sea Port Authority (representing the Ports of Ancona, Falconara, Pesaro, San Benedetto del Tronto, Pescara, Ortona and Vasto, hereafter CAPSA) is also taking part to the

activities, to gain a more in-depth comprehension of the "As Is" situation of digitalization of the above listed ports, in comparison with other Italian and Croatian Adriatic ports, building on available knowledge and having a clearer picture of medium-long-term planning necessary to upgrade the ports' services using technology applications such as DT.

This will help to eventually scale the DT co-design model applied to DIGITPORTS partners, creating a network of digitalized cross-border ports, thus enhancing port's role as engine for growth in the cross-border ecosystem. The port of Ancona is interested in understanding how to potentially mirror the DT implemented in other ports which are destination routes, because it is the main Italian port for international passenger traffic by ferries. Their catchment area and main market is represented by Ro-Ro traffic, with intense traffic flows of trucks and Ro-Ro freight, with the Italian ports of Trieste, Venezia and Ravenna, with Greece (Igoumenitsa and Patras), Croatia (Split) and Albania (Durres). Finally, The Port of Ancona will add on capitalization involving the high training center for seafarers that has already benefitted from the pilot action carried out in INTESA project, e.g. the simulator for training presently used with training purposes.

n.	Associated Organization	Code
A01	Central Adriatic Port System Authority (ports of Ancona, Falconara, Pesaro, San Benedetto del Tronto, Pescara, Ortona and Vasto)	CAPSA

The project's overarching goal is to lead the digital transformation of Adriatic ports through the development and application of digital twin technologies, thus , first and foremost, to review the processes, optimizing the public assets valorization and efficacy of port operations. These tools will facilitate dynamic scheduling, predictive maintenance, real-time decision-making, and integration of administrative and operational processes. By aligning with international best practices, the DIGITPORTS initiative seeks to reduce operational costs, minimize carbon footprints, and improve resource allocation while fostering a sustainable and competitive port ecosystem.

2.3 Goal of the document

The goal of the document is to establish a unified strategic framework for enhancing digitalization within Adriatic ports through the adoption of Digital Twin (DT) technology.

It aims to integrate insights from benchmarking analyses and training sessions to provide actionable recommendations that address operational inefficiencies, foster cross-border collaboration, and support data-driven decision-making. The document will serve as a blueprint for port authorities, ensuring scalability, sustainability, and alignment with international best practices, while addressing the human and technical challenges of transitioning to advanced digital systems.

To this extent, DIGITPORTS local pilot activities will all contribute to creating an open, data-smart common level playing field for final Adriatic ports' users (terminal operators, ship owners, carriers, lorry drivers, passengers of ferry, Ro-Ro or cruises, leisure boaters and tourists, among others).

The DT are the basis for any further development of any Data -driven decision support system to gain a scientific knowledge of their technical and economic performances and to simulate different scenarios to jointly take strategic decisions.

DT technologies, even if applied in different contexts, are particularly important in decision-making, especially in the design and management of complex systems (such as ports are), helping to run several tests with reduced time, public budget and in a safe environment.

The seven DT that will be deployed in the participating Adriatic ports will benefit from a common analysis of the bests AS-IS scenario available now in Europe, and the Cross-Border Scientific Board set up in WP1 will further guide necessary adjustments for the quality and future scalability of the DTs.

The seven DTs pilot actions that will be implemented by DIGITPORTS Consortium will, with their peculiarities, strengthen cooperation in the field of digitalization, creating a better awareness of the technology transfer, hence a deep culture change in organizations.

The local DT will have standard interoperability quality requirements, so to have mid-term goals (10yrs) of Adriatic full digitalization of port operations, in Italy, Croatia and beyond to EUSAIR area (taken into consideration the different levels of entry points).

3. Benchmarking Analysis main findings (D1.1.1)

The benchmarking analysis highlighted critical gaps and opportunities in the digitalization of Adriatic ports, comparing them against leading global ports such as Rotterdam, Singapore, and Hamburg. The findings reveal that while some Adriatic ports have initiated advanced technologies like Port Community Systems (PCS) and Digital Twins, their adoption remains inconsistent and fragmented across the region. Key inefficiencies stem from limited interoperability of systems, underdeveloped data governance frameworks, and insufficient integration of IoT and AI-driven solutions. Cybersecurity and sustainability alignment with international standards, exposing vulnerabilities in an increasingly digital ecosystem.

Best practices from global leaders demonstrate the transformative potential of advanced technologies, showcasing robust data integration, AI-powered logistics, and sustainable operations. These insights underscore the need for a cohesive, phased approach to digital transformation in

Adriatic ports, emphasizing regional cooperation, standardized frameworks, and targeted investments to bridge existing gaps and elevate their global competitiveness.

4. Lesson learned from Training and knowledge transfer sessions (D1.2.1)

The training sessions provided valuable insights into the practical implementation of advanced digitalization techniques and fostered knowledge transfer among Adriatic port authorities, mainly tackling the following issues:

- Digital Twin Concepts and Global use Cases
- Digital Twin at the Port of Rotterdam
- Port of Sines – Digital Strategy and Digital Twin role
- Life Cycle Modelling: Examples of DT Usage in Design, Production and Operations
- Laying the foundation: Imagery technology for DT
- Drone and AI for production and operations
- DT applications for management of construction sites: environmental monitoring and interaction with surroundings
- 3D GIS and migration process from CAD – a case study
- DT as a foundation concept - Nexus Project Perspective
- Digital Twin applications for ports' accessibility, pilot's training, simulations and 3D modelling
- Enabling Stakeholder Engagement
- Internal communications: DT as Cultural Change Driver

Key lessons learned include the importance of adopting interoperable digital solutions, such as Digital Twins and IoT-enabled systems, which demonstrated significant potential to optimize resource allocation, enhance predictive maintenance, and streamline operations.

Training sessions highlighted the necessity of bridging the skills gap within port personnel, emphasizing the critical role of leadership and data-driven decision-making in supporting digital transformation.

Collaborative discussions during the training showcased best practices in sustainability and cybersecurity, underlining the need to align digitalization efforts with environmental goals and robust data protection frameworks. These findings reinforce the importance of a unified approach to

digitalization, with port authorities working collectively to adopt scalable technologies and foster a culture of innovation and adaptability across the Adriatic region.

5. Framework for Digital Twin Applications

5.1 Technical framework for Digital Twin Implementation

The implementation of Digital Twin (DT) technology in Adriatic ports represents a transformative step toward achieving a high level of operational efficiency, sustainability, and competitiveness in the maritime sector. To ensure the success of this endeavor, it is crucial to establish a robust technical framework that incorporates a clear understanding of the technology, sets minimum quality standards, and ensures seamless integration with existing port systems.

Digital Twin technology involves creating a virtual representation of physical assets, systems, or processes that are updated in real-time using data collected from IoT sensors, operational databases, and external sources. In the context of port operations, DT technology enables advanced modeling and simulation of critical components such as terminal layouts, cargo handling equipment, vessel movements, and environmental conditions. This virtual modeling supports real-time monitoring, predictive maintenance, and dynamic resource allocation, significantly enhancing decision-making capabilities.

The DIGITPORTS initiative highlights the potential of DT applications to address operational inefficiencies and reduce bottlenecks in Adriatic ports. By leveraging DT technology, port authorities can simulate various operational scenarios, optimize scheduling for cargo and vessel movements, and improve maintenance planning to minimize downtime. Moreover, DT implementations can play a critical role in supporting sustainability goals, such as energy efficiency and carbon footprint reduction, by enabling precise monitoring and optimization of energy usage.

The technical framework for Digital Twin implementation in Adriatic ports provides a comprehensive roadmap for modernizing port operations and enhancing regional competitiveness. By establishing robust technical standards, ensuring seamless integration with existing systems, and leveraging cutting-edge technologies, the DT framework can transform Adriatic ports into efficient, sustainable, and data-driven hubs. This foundation not only supports immediate operational improvements but also positions the ports for long-term innovation and growth in the global maritime ecosystem.

5.2   Minimum Technical and Quality Standards

For DT technology to deliver its full potential, a set of minimum technical and quality standards must be established. These standards ensure that the technology is scalable, interoperable, and aligned with both regional and international benchmarks. Key technical standards include:

1) Data Integration and Real-Time Processing: The DT system must be capable of collecting, processing, and integrating data from multiple sources, including IoT devices, legacy systems, and external databases, in real time. This ensures accurate and up-to-date information for simulation and decision-making.

2) Interoperability: The DT framework must be designed to integrate seamlessly with existing systems such as Port Community Systems (PCS), customs platforms, and logistics networks. Interoperability is essential for achieving efficient cross-border collaboration and enabling data sharing among stakeholders.

3) Scalability and Flexibility: The DT applications should be scalable to accommodate the diverse needs of different ports and flexible enough to adapt to new technological advancements. This ensures that the framework can support long-term growth and innovation.

4) User-Friendly Interfaces: The design of the DT system must prioritize usability, providing intuitive interfaces for port operators, administrators, and stakeholders to access, analyze, and interact with the digital twin.

5) Security and Compliance: Robust cybersecurity measures must be implemented to protect the integrity and confidentiality of the data processed by the DT system. Compliance with EU data protection regulations, including GDPR, is mandatory.

6) Sustainability Metrics: The DT framework should include integrated tools for tracking and optimizing sustainability metrics, such as energy consumption, waste management, and carbon emissions, to align with the EU Green Deal objectives.

5.3   Integration with existing Port Systems

A critical component of the technical framework is ensuring that DT technology can integrate effectively with existing systems in Adriatic ports. Many ports currently operate with fragmented digital infrastructures, including legacy systems and standalone applications, which can hinder seamless communication and data sharing. To overcome this challenge, the following strategies are proposed:

- Unified Data Platforms: Establishing centralized data platforms that consolidate information from various sources is essential for enabling the DT to function as a comprehensive decision-support tool. These platforms should utilize standard data formats and communication protocols to ensure compatibility.

- IoT Integration: The DT system should leverage IoT devices such as sensors, RFID tags, and GPS trackers to collect real-time data on cargo movements, equipment conditions, and environmental parameters. This integration facilitates accurate modeling and real-time updates.

- AI and Predictive Analytics: Integrating AI-powered analytics into the DT framework enhances its ability to process large volumes of data and generate actionable insights. Predictive analytics can be applied to anticipate equipment failures, optimize resource allocation, and forecast traffic patterns.

- Legacy System Adaptation: To avoid disruptions in ongoing operations, the DT framework should include modules for adapting legacy systems to modern digital standards. This involves creating middleware solutions that bridge the gap between outdated platforms and the DT applications.

- Cross-Border Connectivity: Given the cross-border nature of Adriatic ports, the DT framework must support data sharing and collaboration across national boundaries. This requires harmonizing technical standards and establishing secure, interoperable communication channels.

5.4   Key Technologies Supporting Digital twins

To realize the full potential of DT applications, Adriatic ports need to invest in a range of supporting technologies, including:

- High-Speed Connectivity: Implementing 5G networks to enable low-latency communication between IoT devices, DT systems, and user interfaces.

- Cloud Computing and Edge Computing: Utilizing cloud platforms for data storage and processing, complemented by edge computing for real-time data handling at the source.

- Geographic Information Systems (GIS): Integrating GIS tools to provide spatial analysis and visualization of port layouts, traffic patterns, and environmental impacts.

- Blockchain: Leveraging blockchain for secure data sharing and traceability in supply chain operations.

- Automation Technologies: Incorporating autonomous cranes, vehicles, and drones to enhance operational efficiency and safety.

5.5 Collaborative and Operational Considerations

Effective collaboration and streamlined operations are essential for the successful implementation of Digital Twin (DT) technology across Adriatic ports. A robust framework for cross-border cooperation is necessary to ensure interoperability, data sharing, and unified decision-making among port authorities. This includes establishing standardized protocols for data exchange and fostering partnerships that leverage shared resources and expertise.

Operationally, scalability is a key consideration, ensuring that DT applications can be adapted and expanded across different port environments. Addressing the human factor is equally critical; targeted training programs and leadership development initiatives are needed to bridge the skills gap and enable personnel to effectively utilize advanced digital tools. By prioritizing collaboration and operational readiness, Adriatic ports can maximize the impact of DT technology, achieving greater efficiency and fostering a cohesive digital ecosystem.

5.6 Strategic Alignment and Impact

Strategic alignment is a cornerstone for the successful adoption of Digital Twin (DT) technology in Adriatic ports, ensuring that digitalization efforts are cohesive, scalable, and aligned with broader regional and international goals. The findings from D1.1.1 emphasize the need for Adriatic ports to synchronize their digital strategies with global best practices while addressing region-specific challenges. This includes aligning DT initiatives with sustainability objectives, such as the EU Green Deal, by incorporating renewable energy solutions, reducing carbon footprints, and optimizing resource utilization.

The impact of a unified DT strategy extends beyond individual port improvements. By fostering interoperability and enabling seamless cross-border data sharing, DT applications can enhance regional collaboration and establish the Adriatic as a competitive maritime hub. The integration of

advanced technologies like IoT and AI will empower ports to improve decision-making, reduce operational bottlenecks, and address cybersecurity vulnerabilities identified in the benchmarking report.

Strategically implemented, DT technology not only enhances operational efficiency but also contributes to long-term sustainability and resilience. It positions Adriatic ports as leaders in adopting cutting-edge digital solutions, improving their ability to compete globally while fulfilling environmental and economic objectives. The coordinated adoption of DT applications will ensure that the Adriatic port system evolves into a modern, efficient, and collaborative network that meets the demands of a rapidly changing maritime landscape.

6. Human factor and culture change

The main barrier in full exploitation of advantages of a DT modelling adoption is the human factor, which requires sharing, transparency, trust and accountability to commit to an unprecedented organizational change driver.

The human factor plays a pivotal role in the successful implementation and operationalization of Digital Twin (DT) technology across Adriatic ports. As digitalization accelerates, there is a growing need to address skill gaps, foster a culture of innovation, and empower leadership to drive data-driven decision-making. Without adequately preparing the workforce and leadership structures, the transformative potential of DT technology cannot be fully realized.

The findings from D1.1.1 and related training initiatives emphasize the critical need for comprehensive capacity-building programs. Many port personnel lack familiarity with advanced digital tools, such as IoT-enabled systems, AI analytics, and DT platforms. Targeted training programs, workshops, and certification courses must be developed to bridge these gaps. These programs should focus on equipping employees with practical skills, such as real-time data analysis, predictive maintenance, and operational optimization, ensuring they are fully prepared to manage and leverage DT technology effectively.

But above all, a clear vision is essential for fostering a data-driven culture and ensuring the strategic alignment of digital initiatives.

Port managers and decision-makers must be trained to understand the strategic implications of digital tools, enabling them to make informed decisions that align with organizational goals and broader regional strategies. Leadership training should also emphasize change management, as transitioning to a digitalized environment often requires overcoming resistance and fostering collaboration across departments and stakeholders.

Incorporating DT technology into port operations demands a mindset shift across all levels of the workforce. Encouraging a culture of innovation and adaptability is critical to maximizing the benefits of digitalization. This includes fostering openness to new technologies, embracing continuous learning, and supporting collaborative problem-solving. Highlighting success stories from pilot projects and early adopters within the DIGITPORTS framework can help build confidence and momentum among port personnel.

Rapid digitalization also brings challenges, such as the potential for job displacement and a widening skills gap. To mitigate these risks, efforts must be made to align human resource strategies with technological advancements. Retraining and upskilling existing personnel should be prioritized over hiring external talent, ensuring that the existing workforce remains integral to the transformation process. Furthermore, collaboration with educational institutions and industry partners can provide a pipeline of future talent well-versed in maritime digitalization.

The human factor is not only about operational readiness but also about aligning workforce development with sustainability goals. Promoting environmental awareness and integrating sustainability principles into training programs ensures that port personnel are equipped to contribute to both operational efficiency and ecological stewardship.

By addressing the human factor and investing in leadership, Adriatic ports can ensure a smooth transition to a digitalized environment. Empowered personnel and visionary leaders will play a central role in maximizing the potential of DT technology, fostering a resilient, efficient, and forward-thinking maritime ecosystem.

7. Cross-Border Strategic Recommendations

To achieve a cohesive and efficient implementation of Digital Twin (DT) technology across Adriatic ports, cross-border collaboration must be a central component of the strategy. The geographical and operational interconnectedness of Adriatic ports demands a unified approach that transcends national boundaries, fostering regional cooperation and enabling collective problem-solving. Establishing standardized protocols for data sharing and interoperability is a critical first step. This ensures that ports can seamlessly exchange information and coordinate operations, reducing inefficiencies and supporting real-time decision-making across the region.

The development of a regional digital alliance is essential to facilitate collaborative projects, share best practices, and optimize resource utilization. Such an alliance can serve as a platform for joint innovation initiatives, allowing ports to pool expertise and funding to address common challenges, such as cybersecurity threats, sustainability goals, and workforce training needs. Cross-border collaboration also enhances the scalability of DT applications, enabling smaller ports to adopt proven solutions piloted in larger, more advanced facilities.

To maximize the benefits of this cooperation, Adriatic ports must align their digitalization efforts with broader EU policies and directives, such as the European Green Deal and the Digital Strategy for Europe. This alignment ensures access to funding opportunities and policy support, while also positioning the Adriatic as a unified, competitive maritime corridor on the global stage. By prioritizing cross-border collaboration, Adriatic ports can create a harmonized digital ecosystem that supports sustainable growth, operational excellence, and global competitiveness.

8. Conclusion and Future Outlook

The implementation of Digital Twin (DT) technology across Adriatic ports represents a transformative step toward modernizing operations, enhancing sustainability, and fostering regional competitiveness. Through the adoption of a unified framework, guided by insights from benchmarking, training and knowledge transfer and pilot projects implementation, Adriatic ports are well-positioned to address operational inefficiencies, embrace data-driven decision-making, and align with global best practices.

To position Adriatic ports as leaders in maritime digitalization and sustainability, strategic initiatives must focus on upgrading digital infrastructure and fostering cross-border cooperation and data-sharing frameworks.

The lessons learned and collaborative strategies developed during the DIGITPORTS project will serve as a foundation for long-term innovation, ensuring that ports in the region remain adaptable to technological advancements and resilient to emerging challenges. Looking forward, the continued emphasis on cross-border collaboration, workforce development, and the integration of advanced technologies will not only solidify the Adriatic as a cohesive maritime corridor but also position it as a global leader in smart and sustainable port operations.

This cross-border approach underscores the importance of:

Digital Infrastructure Upgrades: upgrading a port authority's digital infrastructure can act as a facilitator by improving operational efficiency, safety, and sustainability. The adoption of digital platforms and IoT sensors optimizes vessel and cargo traffic management, reducing waiting times and congestion. Digital Twins integration enables advanced simulations for more accurate planning. Enhanced cybersecurity systems protect sensitive data and critical infrastructure. The use of blockchain ensures traceability and transparency in logistics operations. In addition, AI and Big Data solutions foster strategic decisions based on predictive analytics. A modern infrastructure attracts investment, improves competitiveness and supports the green transition with smart grids and optimized energy management.

Cross-Border Cooperation and Data-Sharing Frameworks: Collaborative frameworks for cross-border cooperation and data sharing are essential to creating a unified and efficient Adriatic port network. Establishing a regional digital alliance will facilitate knowledge exchange and enable joint projects that maximize resource utilization. A standardized data-sharing framework supported by robust cybersecurity protocols will ensure secure and seamless integration of information across

ports, enhancing interoperability and decision-making. Cooperation with international partners can also accelerate the adoption of best practices and foster innovation, while alignment with EU regulations and funding mechanisms will provide financial and technical support for these initiatives. By strengthening regional cooperation and leveraging shared resources, Adriatic ports can achieve a more cohesive and competitive maritime ecosystem, ensuring long-term resilience and sustainability.

More effective stakeholder' engagement: using digitalization upgrade to enhance mutual trust among the various parties is very important, using new, easily understandable and specific communication tools that are made possible thanks to DT such as, to name a few: GIS-based DT, interactive infographics, surveys and dashboards, analysis of sentiment on initiatives and changes. These instruments are good means of two-way engagement with the port community and beyond, helping to tell stories to foster public engagement, internal communication and education.

Cultural change: digital transformation will always have a dynamic and direct effect on organizational culture and is not only limited to the potential barriers on technology adoption, and the resistance to innovation. An effective change management policy should strive for transparency, agility, collaboration, and data-driven decision-making. A proactive approach to digital transformation could not only help organizations to adapt to best-practice port operations but also transition to a culture of adaptability, resilience, and continuous improvement.

By implementing pilot projects and investing in staff training, Adriatic ports can build a solid foundation for their digital transformation journey, ensuring both technological and human readiness to meet the challenges and opportunities of the modern maritime landscape.

9. Appendices

9.1 Glossary of Terms

- **AI (Artificial Intelligence)**
  Technology that simulates human intelligence, enabling capabilities like learning, reasoning, and problem-solving. In port operations, AI supports logistics optimization, predictive analytics, and autonomous systems.

- **Baseline Assessment**
  An evaluation conducted at the beginning of a project to determine the current state of systems, operations, or infrastructure. In the DIGITPORTS context, baseline assessments identify existing gaps in digitalization.

- **Blockchain**
  A secure, decentralized digital ledger technology used to record transactions and ensure data transparency. In ports, blockchain improves supply chain security and trust.

- **Carbon Footprint**
  The total greenhouse gas emissions produced directly or indirectly by an entity or activity. Monitoring and reducing carbon footprints is a key aspect of sustainable port management.

- **Cross-Border Collaboration**
  Cooperative efforts between entities in different countries to address shared challenges and goals. In the context of Adriatic ports, it involves harmonizing digitalization strategies and facilitating regional data exchange.

- **Cybersecurity**
  Measures and protocols designed to protect digital systems, data, and infrastructure from unauthorized access and cyber threats. Robust cybersecurity is critical for safeguarding sensitive port operations and data.

- **Data Governance**
  A framework of policies and practices for managing data securely and effectively. Strong data governance ensures data quality, privacy, and compliance with regulations.

- **Digital Twin (DT)**

A virtual representation of a physical asset, system, or process that uses real-time data to simulate, monitor, and optimize operations. In port management, DT technology enables predictive maintenance, resource allocation, and dynamic decision-making.

- **EU Green Deal**

A European Union initiative aimed at making Europe climate-neutral by 2050 through sustainable practices, renewable energy, and reduced carbon emissions. Adriatic ports aim to align their operations with these goals.

- **Geographic Information Systems (GIS)**

Tools used to analyze and visualize spatial data, such as port layouts, traffic patterns, and environmental impacts. GIS enhances planning and decision-making in port operations.

- **Interoperability**

The ability of different systems, devices, or organizations to work together seamlessly. In ports, interoperability ensures efficient integration of digital systems and cross-border data sharing.

- **IoT (Internet of Things)**

A network of interconnected devices and sensors that collect and exchange data in real time. In port settings, IoT devices are used to monitor cargo conditions, equipment status, and energy consumption.

- **Legacy Systems**

Outdated technologies or infrastructure still in use within organizations. Integrating these with modern solutions is a common challenge in the digital transformation of ports.

- **Operational Bottlenecks**

Points in a process where delays or inefficiencies occur, limiting overall productivity. DT technology aims to identify and eliminate these bottlenecks in port operations.

- **Pilot Projects**

Small-scale, initial implementations of a technology or solution to test its feasibility and effectiveness before full-scale deployment. Pilot projects are critical for evaluating DT applications in ports.

- **Port Community System (PCS)**

A centralized digital platform that facilitates communication and data exchange among port stakeholders, such as port authorities, shipping companies, and customs. It improves operational efficiency and streamlines administrative processes.

- **Predictive Maintenance**

  A data-driven approach to maintenance that uses real-time monitoring and analytics to predict potential equipment failures, allowing for timely interventions that reduce downtime and costs.

- **Real-Time Data Processing**

  The ability to collect, analyze, and utilize data immediately as it is generated. In ports, real-time data processing enhances decision-making and operational efficiency.

- **Scalability**

  The capacity of a system or process to expand and adapt to increasing demands. DT applications must be scalable to support growth and ensure broader adoption across different ports.

- **Standardized Protocols**

  Agreed-upon rules and procedures that enable consistent communication and data exchange between systems or stakeholders. These are essential for interoperability in cross-border port operations.

- **Sustainability Goals**

  Objectives aimed at reducing environmental impact, improving energy efficiency, and aligning operations with initiatives like the EU Green Deal. Ports achieve these goals through technologies like renewable energy systems and carbon footprint monitoring.

- **Sustainability**

  Metrics Indicators used to measure environmental performance, such as carbon emissions, energy consumption, and waste management. These metrics help ensure alignment with global sustainability standards.

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