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Study on Enabling Sustainable Management and Development of inland ports

Catalogue of upcoming projects, tools and technologies supporting enhanced interoperability and analysis of process optimisation perspectives

Rotterdam, 21 August 2024

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Summary

This report is part of the "Study in Enabling Sustainable Management and Development of Inland Ports" (Green Inland Ports Study), initiated by the European Commission, within its ongoing efforts to contribute to the achievement of the European Green Deal's (EGD) target of reducing transport-related emissions by 90% by 2050. It is also in line with the Inland Water Transport Digitalisation vision. The importance of inland ports in view of their potential to contribute to the sustainable development and to the objective of reaching the status of zero-emission nodes not just of transport, but also of sustainable industry, clean energy and circular economy, is well recognised in numerous EU policy documents, such as the Sustainable and Smart Mobility Strategy and the NAIADES III action plan.

This report itself represents the Deliverable 3.3: "Catalogue of upcoming projects, tools and technologies supporting enhanced interoperability and analysis of process optimisation perspectives". It contains the findings of the work carried out within Task 3: "Digitalisation", specifically in its Sub-task 3.3: "Process optimisation and interoperability improvement". The main objective of Task 3 is to evaluate the potential of digitalisation to facilitate the greening of port operations, that is, to reduce the overall environmental footprint of port activities, enable multimodality, and promote the sustainable development of inland ports. Digitalisation of inland ports can help reduce port operations-related emissions of various pollutants as it streamlines multiple processes in ports, improves efficiency and productivity, and optimises movements of various crafts in ports, such as vessels, trucks, trains, cranes, and cargo handling equipment. This, in turn, reduces energy consumption and related emissions Digitalisation is the precondition for port automation, where most automated cargo handling equipment are powered by alternative fuels such as electricity.

In addition, the objective of Sub-task 3.3 is to look into new areas and processes that can be digitalised, and to analyse how the existing processes can be optimised, and how could the interoperability of existing systems be improved.

Deliverable 3.3 provides a comprehensive analysis of the future potential of inland port digitalisation, with a focus on process optimisation and systems integration, topped up with an insight into the new projects, tools and technologies in port digitalisation having interoperability as one of their key features. More detailed introduction is given in Chapter 1 of this report.

In view of the future digitalisation potentials, elaborated in Chapter 2, the report analyses digital tools and technologies that are still underused in inland ports, as well as technologies that are relatively recent on the market and are yet to establish themselves firmly among ports and their stakeholders, such as, predictive maintenance, and supply chain visibility, to name a few. Furthermore, the integration of IoT sensors, data analytics, and blockchain technology can transform traditional maintenance practices and enhance real-time tracking of goods. Technologies such as artificial intelligence and drones are also identified as promising tools for addressing operational challenges and improving decision-making processes. From the environmental impact point of view, sustainability dashboards were identified as powerful tools and very convenient solutions for monitoring the overall environmental performance of inland ports.

From the optimisation perspective, tackled in Chapter 3, the deployment of advanced digital tools can streamline various operational processes, automate routine tasks, and enable data-driven decision-making. These improvements can reduce costs, minimise downtime, and enhance overall port efficiency, which, in turn, would have a positive impact on the overall environmental footprint of port operations. In this view, digitalisation can optimise port activities such as traffic management, cargo handling, facilities management, administrative processes, and logistic and value-added processes. Since the digitalisation is a process itself, it is also subject to optimisation, and, in this view, the Study team proposed a 15-steps method for the optimisation of digitalisation processes in inland ports.

Achieving interoperability between different digital tools and systems is of crucial importance for the seamless functioning of port operations within the port boundaries, as well as for the seamless functioning of activities accompanying the flow of goods along the supply chains. Chapter 4 dives deep into details of interoperability challenges, strategic and operational levels of interoperability, strategies for interoperability improvements, and specificities of interoperability between different port systems.

Chapter 5 contains the results of the 2nd survey conducted among port stakeholders in the period of April-May 2024, where participants expressed their own views and experiences on, mostly, digital tools and systems interoperability topics and needs for more intensive usage of existing or additional digital tools.

Upcoming projects, tools and technologies in digitalisation, where one of the research and development areas were the interoperability and/or integration of digital tools, are investigated in Chapter 6, where a selection of European projects and technologies, funded by different public and private funds, was analysed in more details.

Finally, conclusions and key findings of the report are given in Chapter 7.

List of abbreviations

AGV	Automated Guided Vehicle
AI	Artificial Intelligence
AIS	Automatic Identification System
B2B	Business to Business
B2G	Business to Government
CESNI	Comité Européen pour l'Élaboration de Standards dans le Domaine de Navigation Intérieure
CO	Customs Office
CSV	Comma-separated values
DSS	Decision Support Systems
EA	Environmental Authority
EDIFACT	Electronic Data Interchange for Administration, Commerce and Transport
ELD	Electronic Logging Devices
EMS	Environmental Management System
EMT	Environmental Management Tools
EPM	Environmental Performance Measurement
ESB	Enterprise Service Bus
FF	Freight Forwarder
G2G	Government to Government
GNSS	Global Navigation Satellite System
GOS	Gate Operating System
GPS	Global Positioning System
HCN	Hinterland Container Notification
HMO	Harbour Master's Office
HPA	Hamburg Port Authority
HTTP	Hypertext Transfer Protocol
ID	Identification document
IoT	Internet of Things
IT	Information Technology
IWT	Inland Waterway Transport
JSON	JavaScript Object Notation
LL	Living Labs
LTC	Land Transport Companies
M2M	Machine to Machine
ML	Machine Learning
MQTT	Message Queuing Telemetry Transport
OCR	Optical Character Recognition
PA	Port Authority
PAMS	Port Asset Management System
PO	Port Operator
PP	Port Police
QC	Quay Crane
REST	Representational State Transfer

RFID	Radio Frequency Identification
RIS	River Information Services
RMG	Rail Mounted Gantry (Crane)
RTG	Rubber Tyred Gantry (Crane)
RTLS	Real-Time Location System
SA	Ship Agent
SC	Shipping Company
SPL	Smart Port Logistics
TO	Terminal Operator
TOS	Terminal Operating System, Terminal Planning and Operating System
UC	Use Cases
VBS	Vehicle Booking System
VNF	Voies Navigables de France
VTMS	Vessel Traffic Management System
VTS	Vessel Traffic Services
WMS	Warehouse Management Systems
XAI	Explainable Artificial Intelligence
XML	Extensible Markup Language
XPdM	Explainable Predictive Maintenance

1 Introduction

1.1 Overview

Inland ports are crucial nodes of the Trans-European Transport Network (TEN-T). They are indispensable in providing connectivity, sustainable mobility, economic and regional development of the entire EU. They also provide intermodal junctions for at least three different transport modes. Thanks to this particular feature, inland ports contribute to the positive modal shift, shifting the cargo flows from environmentally friendly transport modes (e.g., road transport) to more sustainable ones. This makes them an important tool for achieving the European Green Deal's (EGD)[1] target of reducing transport-related emissions by 90% by 2050. This potential of inland ports has been recognised in EU's policy documents - the Sustainable and Smart Mobility Strategy (SSMS)[2] and the NAIADES III action plan[3]. The SSMS policy document emphasizes the potential of inland ports to reach the status of zero-emission nodes, not only for transport, but also for the sustainable mobility, sustainable industry, clean energy and circular economy. This calls for a new plan for ports to be focused on identifying and implementing environmentally friendly and sustainable solutions, such as energy efficiency, environmental strategies, and monitoring tools to support the transition to renewable energy and zero-emissions port operations.

The roadmap for this plan for ports starts with this study, titled the Study in Enabling Sustainable Management and Development of Inland Ports (Green Inland Ports Study), initiated by the European Commission. This study, with this deliverable being its integral part, has an overarching objective to assist European inland ports in their transformation towards zero-emission sustainable hubs through the assessment of their environmental impact, through the exploration of the role of digitalisation in achieving this objective, and, finally, through the identification of opportunities for integration of inland waterway transport in urban mobility and short distance transport.

In a nutshell, digitalisation of inland ports can help reduce port operations-related emissions of various pollutants as it streamlines multiple processes in ports, improves efficiency and productivity, and optimises movements of various crafts in ports, such as vessels, trucks, trains, cranes, and cargo handling equipment. In such way, energy consumption and related emissions are reduced, even when fossil fuels are used for powering of various vehicles and vessels. In addition, digitalisation is a foundational pillar of automation, and automated cargo handling equipment are increasingly powered by alternative fuels, in most cases electricity.

The topic of digitalisation is the main focus of the Task 3 of this Study. The main objective of Task 3 is to evaluate the potential of digitalisation to facilitate the greening of port operations, that is, to reduce the overall environmental footprint of port activities, enable multimodality, and promote the sustainable development of inland ports. The findings of the Task 3 will be embedded in the

[1] Communication 640 (2019). COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE EUROPEAN COUNCIL, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS - The European Green Deal. Available: https://commission.europa.eu/publications/communication-european-green-deal_en

[2] Communication 789 (2020). COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS Sustainable and Smart Mobility Strategy – putting European transport on track for the future, Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020DC0789

[3] Communication 324 (2021). COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS NAIADES III: Boosting future-proof European inland waterway transport. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52021DC0324

Digitalisation Masterplan for inland ports and terminals and will serve to support and boost the widescale implementation of digitalisation in inland ports across Europe.

This report represents the Deliverable 3.3 “Catalogue of upcoming projects, tools and technologies supporting enhanced interoperability and analysis of process optimisation perspectives”, which is the result of the work performed in the Sub-task 3.3: “Process optimisation and interoperability improvement”. In this view, the objective of Sub-task 3.3 is to look into new areas and processes that can be digitalised, and to analyse how the existing processes can be optimised, and how could the interoperability of existing system be improved. It therefore reflects on topics such as further digitalisation needs and potentials, optimisation perspectives, interoperability issues, and the ongoing and upcoming projects and technologies in port digitalisation having the achievement of interoperability between ports’ digital tools as one of their goals. The findings of this deliverable will feed into the Sub-task 3.6 (Digitalisation Masterplan) as inputs for the digitalisation vision, strategy, roadmap and related action plan, as well as for the digitalisation guidelines.

Results of the work in this Sub-task are to be presented to relevant stakeholders during the events organised by the Study team in Task 5.

1.2 Further opportunities in inland port digitalisation

In recent years, the digital transformation of inland ports has revolutionised traditional port operations, enhancing efficiency, visibility, and sustainability across various processes. However, there are still, on the one hand, significant opportunities for further digitalisation beyond the processes currently undergoing transformation, and increased use of existing digital technologies, on the other hand.

One of the key areas with significant potential for further digitalisation is predictive maintenance. The deployment of IoT sensors, combined with data analytics and predictive modelling, allows inland ports to shift from reactive maintenance practices to proactive strategies that anticipate equipment failures before they occur. Predictive maintenance minimises downtime, reduces maintenance costs, and extends the lifespan of critical assets, ensuring the smooth and reliable operation of port facilities.

Supply chain visibility is another area to be further explored in inland ports. Integrating digital technologies with transportation modes such as rail and road provides stakeholders with real-time visibility into the movement of goods, enabling better coordination, optimisation, and decision-making throughout the supply chain. Enhanced visibility not only improves efficiency but also enhances customer satisfaction by reducing delays and uncertainties on the one hand, and increasing predictability and plannability, on the other hand.

Furthermore, inland ports can leverage novel technologies such as blockchain, artificial intelligence, and drones to address various challenges and seize new opportunities. Blockchain technology can enhance transparency, security, and efficiency in supply chain transactions, while AI-driven analytics can optimise operational processes and improve decision-making. Drones can be deployed for surveillance, security, and infrastructure inspection, enhancing safety and operational effectiveness within port facilities.

The journey towards digital transformation in inland ports is an ongoing process, with vast potentials yet to be realised. Setting their mindset towards innovation, collaboration, and a forward-thinking mindset, inland ports can use digital technologies to unlock new efficiencies, drive sustainable growth, and maintain their position as efficient nodes in the global supply chain network.

1.3 Optimisation perspectives

The use of advanced technologies and innovative solutions in digitalisation facilitates the optimisation of various operational processes in ports, automation of routine and repetitive tasks, as well as data-driven decision-making. In this view, digitalisation can assist in the following core processes in ports:

- traffic management, such as berth scheduling, vehicle appointment processes, gate access, internal road and rail traffic processes, and traffic of cargo handling equipment,
- cargo handling processes, including ship-to-shore loading/unloading and movement of cargo between the quay and storage areas,
- infrastructure, suprastructure, and equipment management,
- logistic and value-added processes,
- administrative tasks.

Limited number of berths at certain ports and terminals makes the berth scheduling the most critical aspect of traffic management in ports. Digital tools can facilitate dynamic berth scheduling systems that can use various parameters, such as vessel arrivals, cargo types and terminal capacity in real time, as inputs for their scheduling algorithms. These scheduling algorithms optimise berth utilisation, minimising vessel waiting times and reducing congestion, which leads to shorter vessel turnaround times and maximised berth throughput. This, in turn, leads to lowered fuel consumption and consequently to the reduction of emissions of pollutants.

Another important process in the domain of traffic management in ports is a vehicle appointment process. Specialised digital tools allow trucking companies and other stakeholders to schedule cargo pickups and deliveries well in advance. When fed with the necessary input data (whether manually or via sensors), these digital appointment systems provide visibility into time slot availability, thus allowing efficient booking and minimising congestion at the port gates. Thanks to these features of such systems, they are often integrated with gate operating systems that are used to automate the entry and exit of vehicles in/out of port areas.

In addition, digital tools used for real-time monitoring of internal road and rail traffic within port boundaries greatly help in route optimisation and congestion avoidance. These tools use different technologies to collect static and dynamic data to identify congestion hotspots and reroute traffic to avoid bottlenecks. Apart from traffic optimisation achieved in such way, these tools increase overall efficiency and safety. Finally, these tools can also optimise the movement of cargo handling equipment, automating routing and prioritising tasks on the basis of specific cargo handling requirements.

Digitalisation can also optimise crane operations, thanks to the real-time monitoring of crane movements and positions, feeding this data into terminal operating systems. This enables features such as precise control of crane movements, collision avoidance, and improved safety and efficiency.

As elaborated in the further sections of the report, digitalisation can optimise infrastructure, suprastructure and equipment in terms of use and maintenance, the logistics processes such as inventory management, labelling, packing, etc.

Finally, digital tools can optimise administrative tasks through digital document management, electronic invoicing or online permit applications.

It needs to be noted that digitalisation processes themselves can be optimised in order to ensure full compliance with the digitalisation objectives. This includes a strategic alignment of digitalisation objectives with the port's business objectives, involvement of stakeholders, and evaluation of applied technologies. Effective data management and cybersecurity are of paramount importance, as well as compliance with regulations and resource allocation. Continuous improvement through performance metrics and fostering digital culture are crucial for successful digitalisation process in ports. This comprehensive approach ensures that inland ports can achieve optimal digitalisation, thereby improving their efficiency and environmental footprint while addressing evolving stakeholder needs.

1.4 Interoperability issues

In complex port systems, where there are more than one digital tool or technology applied, interoperability between those tools comes into focus as it may become a cornerstone of efficient and effective port operations, facilitating seamless integration and communication between various digital tools and systems. This connectivity between different digital tools and systems is important across different types of port systems, including single inland ports, EU inland port systems, EU inland ports and connected EU seaports, and inland ports and stakeholder systems. Functional interoperability between relevant digital tools allows ports to optimise their operations, enhance data exchange, and improve overall efficiency of supply chains in which ports are included.

For the purposes of this report, interoperability between digital tools has been examined in terms of the challenges of interoperability, its definitions and basic aspects, strategic and operational levels, and in terms of strategies for interoperability improvements.

To achieve seamless interoperability of various digital tools along the supply chain, it is essential to consider interoperability at two distinct levels: strategic and operational. This dual approach recognises the different yet complementary roles that each level plays in facilitating the smooth integration and functioning of involved digital tools. Achieving interoperability at both strategic and operational levels allows ports to fully benefit from digitalisation processes. It facilitates the creation of efficient and collaborative networks with a myriad of stakeholders, improving overall operational efficiency.

Main goals of digital interoperability of different digital tools used in inland ports encompass enabling quick, seamless, secure, and reliable data and information exchange among users involved in port operations and the broader supply chain. Inland ports have at their disposal various strategies aimed at achieving this level of interoperability. In a nutshell, these strategies benefit not only the ports but also all stakeholders and end users and they include both technical and organisational measures.

In single inland ports, port operations are typically performed by various stakeholders, such as port authorities, port and terminal operators, whereas each of these actors deploy different digital tools. These tools may include Port Community Systems (PCS), Terminal Operating Systems (TOS), Gate Operating Systems (GOS), data analytics platforms and predictive maintenance tools, to name a few. To achieve interoperability between these digital tools is of crucial importance for several reasons, including enhanced operational efficiency, improved data accuracy and availability, smooth exchange of data between complementary tools, and cost reductions due to avoidance of multiple data re-entry into each tool.

In wider port systems, such as EU inland port systems located on the same waterway or in the same region, interoperability of digital tools deployed in individual ports of such systems provides benefits that include, coordinated operations, improved competitiveness, streamlined cargo handling, and resource optimisation thanks to share information and coordinated planning.

Apart from physical connectivity of EU inland ports and connecting EU seaports through direct rail, road, or inland waterway connections, or logistical connectivity, via regular shuttle/feeder services provided by various operators, these ports can also be connected through digital tools. Such connection creates a more integrated and efficient transport network. Benefits of digital connectivity of EU inland ports and connecting EU seaports include the integration of supply chains, efficient cargo transfer, improved visibility in terms of cargo tracking, and environmental benefits resulting from optimised transport routes and reduced dwell times.

Finally, the integration of digital tools in inland ports and stakeholders' systems (such as trucking companies, rail operators, shipping companies, freight forwarders, logistic operators, etc.) is vital for efficient management of modern supply chains. Achieving interoperability between digital tools in these systems can bring tangible benefits for all users, including improved coordination of transport schedules and logistic activities, reduced waiting times for trucks, trains and vessels, improved customer service in terms of real-time information sharing and enhanced transparency, cost savings due to efficient coordination and reduced delays, and, last but not least, environmental benefits resulting from optimised movements and reduction of waiting times.

1.5 A look beyond the horizon

Finally, a look at the latest projects, tools and technologies aimed at exploring the frontiers of inland ports digitalisation, with a special focus on optimisation, integration and interoperability, crowns the deliverable. Both national and supranational authorities and financing institutions are fortunately aware of the importance of digitalisation in inland ports, and in transport chains as a whole, resulting in numerous programmes aimed at co-financing relevant projects in port digitalisation. These projects are aimed at preparing the industry for advanced digitalisation, automation and autonomation of ports and supply chains in general, increasing transparency and digital integration of different transport modes taking part in supply chains, as well as at solutions for effective, efficient and sustainable multimodality where ports are involved.

Many ports and other stakeholders understand the importance of integration of digital tools, especially in cases where healthy and usual competition between ports, or between other transport operators, remains unhindered, and at the same time offering possibilities for cooperation in mutual interest – leading to the so-called "coopetition"[4] between ports and/or between relevant stakeholders. This phenomenon resulted in numerous technologies, projects and digital tools providing integration, collaboration and digital compatibility between ports and different stakeholders. Digital platforms offering connection and integration of various apps, sensors and software, sensor technology and artificial intelligence combined into predictive maintenance tools, multimodal transport planning tools, common PCS for inland ports and connected seaports, smart docks integrating cameras, software and sensors are just a few interesting examples of the digital technologies appearing on the horizon.

[4] Song, D. W. (2003). Port co-opetition in concept and practice. *Maritime Policy & Management*, 30(1), 29–44. Available: https://doi.org/10.1080/0308883032000051612

2 Further digitalisation needs and potentials

2.1 Digitalisation needs resulting from the 1st survey

This section contains responses to the questions on digitalisation needs of inland ports in Europe and across the globe, launched in the 1st survey from June 2023. The total number of relevant respondents to the 1st survey included 26 different port authorities and port operators, while 13 port authorities and port operators responded to the question on their further digitalisation needs. Their responses are summarised in the following table:

Table 2.1: Further digitalisation needs of responding inland ports

Country	Port	Respondent	Digitalisation needs
AT	Enns	Container Terminal Enns GmbH	• Optical Character Recognition (OCR) systems for trucks and trains. • Crane management digital tool. • Truck management digital tool. • Paperless in/out document exchange.
AT	Enns	EHG Ennshafen GmbH	• Completion of the digital booking platform.
FR	Lille	Ports of Lille	• Realtime monitoring of operational activities on terminal. • Predictive maintenance of engines and warehouses. Digital twin applied on operational activities. • Environmental surveillance. • Energy management system. • Drone surveillance. • Inter-operability of different IT systems throughout the supply chain.
FR	Rhône ports	Compagnie Nationale du Rhône	• Tracking and monitoring of all transport modes • Precise statistics on different types of freight / Digitalisation of administrative procedures (customs, etc.) • Digital platform for the tracking & exchange of shipping documents.
FR	Seine-Escaut canal ports	Syndicat Mixte Docks Seine Nord Europe Escaut	• Cargo community system. • Berthing application.
FR	Le Havre, Rouen, Pairs	Grand Port fluvio-maritime de l'axe Seine - HAROPA PORT	• Port Community System upgrade. • Digital twin. • Cybersecurity management.
DE	Trier	Hafen Trier GmbH	• Digital twin. • OCR for trains and rail traffic management platform.
DE	Minden	Mindener Hafen GmbH	• Digital terminal. • Digital forecasting of estimated time of arrival. • Predictive maintenance.
DE	Wesel	DeltaPort GmbH & Co. KG	• Terminal Operating System. • Connected digital ports & collaborative tool.

Country	Port	Respondent	Digitalisation needs
			• Multimodal digital platform.
DE	Duisburg	Duisburger Hafen AG	• Port management and information system. • Digital communication tool between the port and shipping industry. • Multimodal digital platform.
HU	Dunaújváros	Centroport Kft.	• RIS based traffic planning and management tool.
NL	Utrecht	Havendienst gemeente Utrecht	• Digital platform for port dues calculation and invoicing.
VN	Haiphong	Port of Haiphong	• Terminal Operating System upgrade. • Digital platform for stakeholders connection.

Source: Consortium.

From the above table it can be concluded that the participating inland ports are highly aware of the potentials of port digitalisation and the benefits of such transformation. Nevertheless, the results need to be taken with a certain reserve due to the fact that mostly ports from highly industrialised countries responded the question on the digitalisation needs.[5]

2.2 Further digitalisation potentials

In this section, only a selection of digitalisation technologies is elaborated, primarily due to extremely high number of technologies that can be digitalised using one or more available digital solutions.

In recent years, the digital transformation of inland ports has revolutionised traditional port operations, enhancing efficiency, visibility, and sustainability across various processes. However, there are still significant opportunities for further digitalisation, beyond the processes that are already undergoing digital transformation.

While processes such as document management, berth planning, truck management, and yard planning have already seen digitalisation efforts, there remain untapped areas where digital technologies can bring additional benefits. Wide scope of available advanced digital solutions enables inland ports to unlock new opportunities for optimisation, innovation, and competitiveness in the ever-evolving landscape of supply chains and logistics.

One of the key areas with significant potential for further digitalisation is predictive maintenance. Carefully distributed IoT sensors, as well as the data analytics, and predictive modelling, allow inland ports to improve their maintenance policies, from reactive maintenance practices to proactive strategies that anticipate equipment failures before they occur. Predictive maintenance not only minimises downtime and reduces maintenance costs but also extends the lifespan of critical assets, ensuring the smooth and reliable operation of port facilities.

Supply chain visibility is another area suitable for digital innovation in inland ports. Beyond the port gates, integrating digital technologies with transportation modes such as rail and road can provide stakeholders with real-time visibility into the movement of goods, enabling better coordination, optimisation, and decision-making throughout the supply chain. Enhanced visibility not only improves efficiency but also enhances customer satisfaction by reducing delays and uncertainties.

[5] Ecorys, et.al. (2023). Inventory of port cooperation and collaboration systems, digital tools and applications and assessing their effect on greening and economic sustainability objectives, Deliverable D 3.2 of the *Study on Enabling Sustainable Management and Development of Inland Ports*, funded by the European Commission.

Furthermore, inland ports can use other novel technologies such as blockchain, artificial intelligence, and drones to address various challenges and seize new opportunities. Blockchain technology, for example, can enhance transparency, security, and efficiency in supply chain transactions, while AI-driven analytics can optimise operational processes and improve decision-making.

Drones can be deployed for surveillance, security, and infrastructure inspection, enhancing safety and operational effectiveness within port facilities.

The journey towards digital transformation in inland ports is an ongoing process, with vast potentials yet to be realized. By embracing innovation, collaboration, and a forward-thinking mindset, inland ports can leverage digital technologies to unlock new efficiencies, drive sustainable growth, and maintain their position as indispensable nodes in the global supply chain network.

In this section, the Study team aims to present a selection of digitalisation technologies that still offers untapped potential for improvement of operational and management efficiency of inland ports.

Table 2-2 Selection of digital technologies for further digitalisation of inland ports

Digitalisation areas	Benefits for inland ports
Predictive maintenance	Implementing IoT sensors and predictive analytics can help in monitoring the condition of machinery, equipment, and infrastructure within the port. This can predict maintenance needs, reduce downtime, and optimise resources.
Supply chain visibility and resilience	Digitalising supply chain processes beyond the port gates, integrating with transportation modes like rail and road, and providing real-time visibility to stakeholders can enhance efficiency, reduce delays, and improve customer satisfaction.
Blockchain for supply chain transparency	Implementing blockchain technology for supply chain transparency and traceability can enhance trust among stakeholders, streamline documentation processes, and reduce the risk of fraud or errors.
Drone surveillance	Employing drones for surveillance and security purposes can improve monitoring of port facilities, perimeter security, and response to incidents, thereby enhancing safety and security.
Data analytics for operational optimisation	Use of big data analytics and machine learning algorithms to analyse operational data can optimise resource allocation, improve productivity, and identify opportunities for process optimisation within the port.
Digital twin technology	Creating digital twins of port infrastructure and operations can enable simulation, visualisation, and optimisation of port processes, leading to better decision-making, risk management, and performance improvement.
Customs and regulatory compliance	Streamlining customs clearance processes through digital platforms, integrating with customs authorities, and automating regulatory compliance procedures can reduce clearance times, minimise paperwork, and enhance trade facilitation.
Position detection systems	Knowing the exact location and movement history of a cargo parcel enables faster cargo delivery from the yard to the gates, as well as increase of safety and security aspects. It also prevents cases of misplaced or lost containers in ports.

Digitalisation areas	Benefits for inland ports
Automated terminals and smart ports	Implementing automation for intra-port cargo handling can enhance efficiency, reduce labour costs, and improve safety by automating the movement of goods within the port area. Both digitalisation and automation are important foundation elements of smart ports.
Robotic vessels as a service	Robotic unmanned vessels, equipped with various sensors and transmitting devices can perform various tasks in ports, such as quay or hull inspections, grounding avoidance, air and water quality measurements and all sorts of data collection.

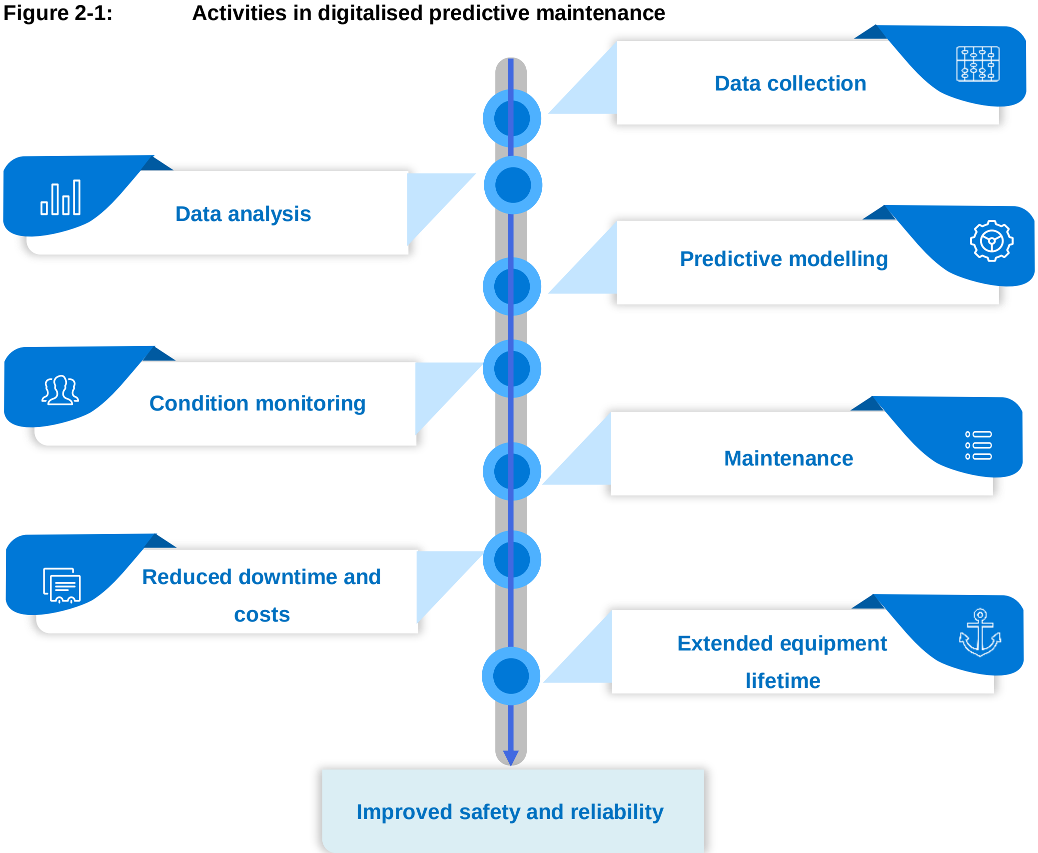
Source: Consortium.

2.2.1 *Predictive maintenance*

Predictive maintenance is a proactive maintenance strategy that utilises data analysis and predictive modelling to forecast equipment failures before they occur. In inland ports, predictive maintenance can be applied to various types of machinery, equipment, and infrastructure within the port premises, including cranes[6], conveyor systems, forklifts, other cargo handling equipment, rail tracks, and even buildings.

In general, the predictive maintenance typically follows the following pattern of activities:

Figure 2-1: Activities in digitalised predictive maintenance



Source: Consortium.

[6] Oladugba, A., Gheith, M. and Eltawil, A. (2020). An IoT Based System Predictive Maintenance and Operations Scheduling System for Yard Crane Control in Container Terminals, Conference paper, *29th International Conference of International Association for Management of Technology* (IAMOT)

Data collection: Inland ports can install sensors and IoT devices on critical assets to collect real-time data on various parameters such as temperature, vibration, pressure, mechanical stress, lubrication levels, and various operating conditions. These sensors continuously monitor the health and performance of equipment.

Data analysis: The data collected from sensors are transmitted to a central database or cloud-based platform where advanced analytics techniques, including machine learning algorithms, are applied to analyse the data. Patterns, trends, anomalies, and early indicators of potential failures are identified through data analysis.

Predictive modelling: Based on historical data and patterns identified through analysis, predictive models are developed to forecast equipment failures and predict remaining useful life (RUL) of assets. These models consider various factors such as operating conditions, maintenance history, environmental factors, and asset-specific characteristics.

Condition monitoring: Predictive maintenance systems continuously monitor the condition of equipment in real-time and generate alerts or notifications when deviations from normal operating conditions are detected.[7] Maintenance teams can receive early warnings about impending failures and take preventive actions before breakdowns occur.

Maintenance planning: Armed with predictive insights, maintenance teams can plan maintenance activities more efficiently. Instead of performing maintenance on a fixed schedule or reacting to failures after they occur, resources can be allocated based on actual equipment condition and predicted failure probabilities. This helps in optimising maintenance schedules, minimising downtime, and reducing maintenance costs.

Reduced downtime and costs: By identifying potential failures in advance, predictive maintenance helps in avoiding unplanned downtime and costly emergency repairs. Equipment failures can be addressed during scheduled maintenance windows, resulting in minimal disruption to port operations and reduced overall maintenance costs.

Extended equipment lifespan: Proactively addressing maintenance needs based on predictive insights can extend the lifespan of equipment and infrastructure within the port. By addressing issues before they escalate, predictive maintenance helps in preserving asset integrity and reliability over time.

Improved safety and reliability: Predictive maintenance contributes to improved safety by reducing the likelihood of equipment failures and accidents. It enhances the reliability of critical assets, ensuring smooth and uninterrupted operations within the port environment.

Predictive maintenance empowers inland ports to transition from reactive and time-based maintenance approaches to proactive and data-driven maintenance strategies, leading to improved operational efficiency, cost savings, and asset performance optimisation.

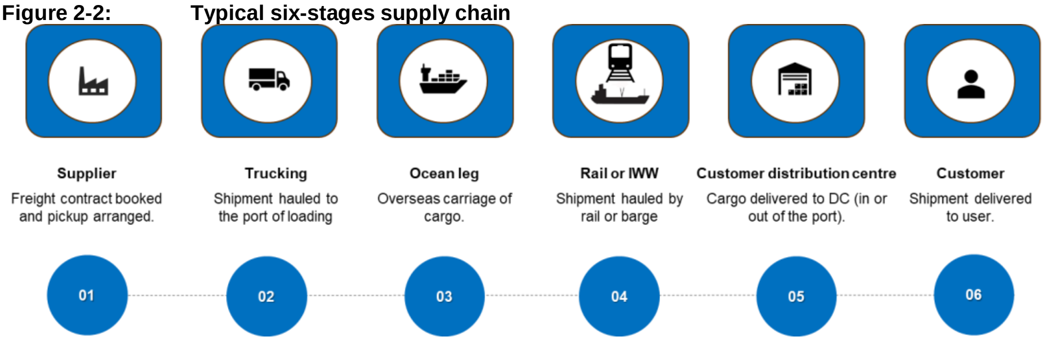
Predictive maintenance leads to a significant reduction in equipment downtimes, typically by 30-40%[8], consequently lowering the demand for replacement parts manufacturing and transportation. This reduction in downtime not only saves on materials but also contributes to a decrease in emissions associated with the manufacturing and transportation processes.

[7] https://www.ericsson.com/en/blog/2022/8/iot-condition-monitoring-smart-ports
[8] https://netzero-events.com/port-digitalization-for-efficiency-and-emission-reduction/

2.2.2 Supply chain visibility and resilience

Supply chain visibility (SCV) is the knowledge, traceability and understanding of operations throughout an entire supply chain (including all stages and operational processes) from production to consumption, that is, from source to sink. From the point of view of digitalisation, the following definition is the most interesting one: Access to high quality *information* that describes various factors of demand and supply. In order for *information* to be of high quality, it must be accurate, timely, complete and in usable *forms*".[9]

Figure 2-2: Typical six-stages supply chain



Source: Consortium.

In the context of inland ports, enhancing supply chain visibility involves digitalising processes beyond the port gates and integrating with various transportation modes, including rail and road, to provide real-time visibility to stakeholders.

Supply chain visibility includes the following features and benefits:

End-to-end visibility: Supply chain visibility enables stakeholders to have a comprehensive view of the entire supply chain process, including the status and location of goods, inventory levels, transportation schedules, and order fulfilment progress. This visibility extends beyond the boundaries of the inland port to encompass upstream suppliers, downstream customers, and transportation partners.

Real-time tracking: Digital technologies such as IoT sensors, RFID tags, GPS tracking, and telematics enable real-time tracking and monitoring of goods as they move through different stages of the supply chain. This real-time visibility allows stakeholders to proactively identify issues, anticipate delays, and make informed decisions to optimise logistics operations.

Improved coordination: Through the integration of data from multiple sources and stakeholders, supply chain visibility facilitates better coordination and collaboration among various parties involved in the supply chain, including shippers, carriers, freight forwarders, customs authorities, and warehouse operators. This seamless flow of information enables smoother transitions between different transportation modes and facilitates efficient order fulfilment processes.

Reduced delays and disruptions: With greater visibility into the supply chain, stakeholders can quickly identify potential bottlenecks, disruptions, or delays and take proactive measures to mitigate risks and maintain supply chain continuity. When various issues are addressed in real-time, supply chain visibility can help minimise lead times, reduce stockouts, and improve on-time delivery performance.

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[9] Williams, B.D., Roh, J., Tokar, T., Swink, M. (2013). Leveraging supply chain visibility for responsiveness: The moderating role of internal integration. *Journal of Operations Management*, 31 (7-8), 543–554. Available: https://doi.org/10.1016/j.jom.2013.09.003

Enhanced customer satisfaction: Real-time visibility into order status and shipment tracking enables improved customer communication and transparency. This enables customers to track their orders in real-time, receive accurate delivery estimates, and be notified of any delays or exceptions. This enhanced visibility and communication lead to higher levels of customer satisfaction and loyalty.

Data-driven insights: Supply chain visibility generates a wealth of data that can be analysed to gain valuable insights into supply chain performance, trends, and opportunities for improvement. By leveraging advanced analytics and predictive modelling, stakeholders can identify patterns, optimise resource allocation, and make data-driven decisions to enhance overall supply chain efficiency and resilience.

Regulatory compliance: Supply chain visibility also helps ensure compliance with regulatory requirements and industry standards, such as customs regulations, trade compliance, and safety regulations. By maintaining accurate and up-to-date records of goods movement and documentation, inland ports can streamline customs clearance processes and avoid costly penalties or delays.

Enhancing supply chain visibility through digitalisation enables inland ports to optimise logistics operations, improve efficiency, reduce costs, and enhance customer satisfaction. By leveraging real-time data and collaboration across the supply chain ecosystem, stakeholders can unlock new opportunities for innovation and competitiveness in the global marketplace.

Supply chain resilience refers to a supply chain's ability to bounce back quickly from disruptions while maintaining operations and meeting customer demands. It relies on flexibility, redundancy, visibility, collaboration, risk management, and adaptability to withstand challenges and uncertainties effectively. Resilient supply chains are agile, proactive, and adaptable, ensuring stability, sustainability, and customer satisfaction in a dynamic business environment.

Naturally, the digitalisation of supply chain beyond the port area is not the sole responsibility of inland ports. This is why collaboration with external stakeholders is of crucial importance for the benefit of all. From the perspective of supply chain resilience, digitalisation of the overall supply chains can bring the following benefits:

- Dynamic route planning: Real-time visibility into transportation modes such as rail and road allows inland port operators to dynamically plan and optimise transportation routes. In the event of disruptions like road closures or traffic congestion, alternative routes can be quickly identified to ensure the timely movement of goods to and from the port.
- Inventory optimisation: Digitalisation enables better management of inventory levels within inland port facilities. By integrating data from suppliers, manufacturers, and distribution centres, inland port operators can optimise inventory levels and buffer stock to mitigate supply chain disruptions and ensure continuous availability of goods.
- Collaborative risk management: Digital platforms facilitate collaboration and information sharing among supply chain partners, including shippers, carriers, and logistics providers. By sharing real-time data on inventory levels, transportation schedules, and demand forecasts, stakeholders can collectively identify and address risks to ensure the resilience of the inland port supply chain.
- Alternative mode integration: Digitalisation enables seamless integration with alternative transportation modes such as rail or truck. In the event of disruptions, inland port operators can quickly switch to alternative modes to maintain supply chain continuity and minimise disruptions to cargo movements.

- Demand sensing and forecasting: Real-time visibility into cargo movements and demand patterns allows inland port operators to anticipate changes in demand and adjust operations accordingly. By leveraging data analytics and machine learning algorithms, operators can optimise resource allocation, improve forecasting accuracy, and respond rapidly to fluctuations in demand to ensure supply chain resilience.
- Continuous monitoring and adaptation: Digitalisation enables continuous monitoring of key performance indicators (KPIs) within the inland port operations. By tracking metrics such as throughput, turnaround times, and equipment utilisation in real-time, operators can identify bottlenecks, optimise processes, and adapt strategies to enhance resilience and efficiency.
- Supplier and vendor diversification: Digital platforms facilitate the identification and onboarding of alternative suppliers and vendors. Inland port operators can leverage digital tools to assess supplier performance, evaluate risk exposure, and diversify their supplier base to reduce dependency on a single source and enhance resilience in the face of supply chain disruptions.

To develop a sustainable digitalisation capability for supply chain resilience, terminal operators offering additional logistic services must leverage key value levers such as a robust digital backbone, a digital twin, and an enhanced digital workforce.[10]

Digital backbone

In order to achieve end-to-end supply chain visibility, inland ports, as well as other logistic operators within the supply chain, must capture vast amounts of real-time data (inventory, delivery, weather, production, worker availability, sales, etc.) all along their supply chains. This includes data collected from different sources, such as radio frequency identification (RFID) tags, global positioning systems (GPS), loyalty cards and Point of Sale (POS) transactions, and data emitted by social media feeds and equipment sensors. From the collected data, inland ports along with logistic operators could utilise artificial intelligence, machine learning, and other game-changing data analytics to gain better insight into supply chain operations and provide better value-added services to customers. For example, data collected on suppliers' on-time deliveries, average delays, and degree of inconsistency are valuable to logistic operators in making inventory decisions, such as how much extra stock needs to be held, where it should be held, and when to hold it to keep the supply chain running reliably.

Hence, a supply chain "digital backbone" is needed to coordinate the seamless collection, sharing, and integration of data along the supply chains. Inland ports need to establish the key digital technologies that contribute to the entire supply chain ecosystem so that sensors in different domains and platforms can connect to/communicate with each other and so that inland ports and other authorised stakeholders can have access to data in real time. The digital backbone is a secure, inland port-specific digital architecture that is comprised of smart platforms, cloud-based applications, automation, and lean processes. Inland ports, logistic operators and other relevant stakeholders need the digital backbone to deliver real-time supply chain visibility to mitigate uncertainties. Apart from linking the technologies and data collection sensors, a digital backbone should also drive real-time interoperability across domains and platforms of the supply chain stakeholders (suppliers, partners, logistic providers, and customers).

Developing one's own cloud and platform systems may be costly and time-consuming. Therefore, inland ports and other stakeholders could leverage and take advantage of existing innovative Platform-as-a-Service (PaaS) and Software-as-a-Service (SaaS) solutions available in the market. When evaluating the option, inland ports need to assess the cost and speed of deployment as well as the pros and cons of public and private cloud and data centres.

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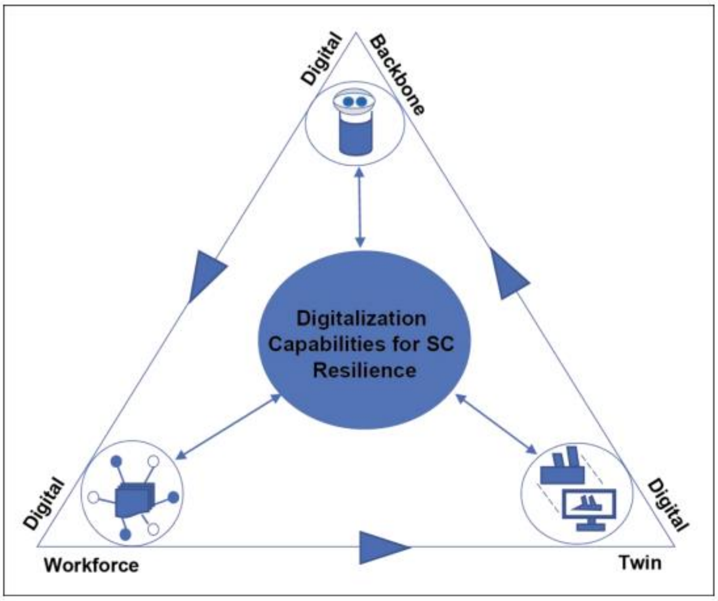
[10] Tan, K.H. (2023). Building Supply Chain Resilience with Digitalization, ADBI Working Paper 1389. Tokyo: Asian Development Bank Institute. Available: https://doi.org/10.56506/MRAJ3174

Figure 2-3: Digitalisation capabilities for supply chain resilience



Source: Tan, K.H.

Digital twin

Given the rapidly changing business environment and the frequency of disruptions, traditional theoretical modelling and simulation methods to enhance supply chain resilience are no longer sufficient. When intricate, interconnected events interact, existing model-based systems lack the closed-loop information control capabilities needed to manage uncertainty during disruptions. To proactively strengthen supply chain resilience, stakeholders must adopt a digital supply chain twin - a digital replica of the physical supply chain. This twin collects real-time information from physical supply chains, including transportation status, production levels, customer demand, and inventory levels, enabling firms to monitor and make informed decisions.

Through the digital twin, operators can simulate supply chain operations, evaluate disruption propagation, and assess their impact. This allows firms to model and predict the relative impact of various sources of uncertainty, as well as measure the indirect effects on downstream or upstream segments of the supply chain. Consequently, proactive recovery policies, remedial measures, and contingency plans can be formulated to address identified disruptive events. Inland ports can also analyse the potential impact of adjusting inventory parameters across supply chains on costs and customer service.

To fully realise the benefits of the supply chain digital twin, data sources enabled by the digital backbone must be seamlessly integrated and continuously updated in real time. Additionally, digital twins for products and infrastructure complement supply chain twins. For example, a product digital twin can expedite product development and improve quality by enabling rapid iterations and optimisations of designs and manufacturing processes, thus reducing time to market.

However, the effectiveness of the supply chain digital twin heavily depends on the availability of high-quality data from multiple sources. Furthermore, leveraging the full potential of the digital twin often requires a highly skilled workforce with strong simulation and analytics capabilities.

Digital workforce

Cloud platforms and suites of Software-as-a-Service (SaaS) team productivity applications serve as the fundamental infrastructure for driving supply chain digital transformation. It goes without saying that the expertise and proficiency of an organisation's workforce in areas such as artificial intelligence, machine learning, data analytics, and process automation are crucial for sustaining this digital transformation. Therefore, enhancing workers' digital capabilities to meet the demands of the digital era is essential for ensuring supply chain resilience. The successful adoption of digital technologies and workers' adeptness in utilising them are pivotal for achieving a successful digital transformation.

Furthermore, given the rapidly evolving landscape of digital technologies, organisations must continuously develop strategies to reskill their workforce to ensure that they possess the appropriate capabilities, size, and expertise in digital skills. There is no one-size-fits-all approach to enhancing workers' digital skills. Operators may opt to nurture talent internally or through external channels such as apprenticeships and graduate programs. While organisations may enlist external talent to address immediate digital skill gaps, it is equally important to devise a roadmap for effectively upskilling the existing workforce.

It is evident that a high level of digital skills among workers is integral to an organisation's digital transformation journey. Therefore, implementing robust talent management strategies and incentive schemes becomes imperative in this context.

2.2.3 Blockchain for supply chain transparency

Blockchain technology presents a promising solution for revolutionising Supply Chain Management (SCM), offering organisations the potential to enhance transparency, traceability, and efficiency across their supply chains. By leveraging this technology, organisations can more easily track goods from their origin to their destination, promptly identify any issues along the way, and securely record transactions, thus establishing an immutable record of all activities within the supply chain.

Moreover, blockchain technology ensures that all involved parties remain informed about developments at each stage of the supply chain, consequently reducing errors, increasing efficiencies, and saving costs. This, in turn, contributes to the establishment of secure yet transparent supply chains.

For supply chain companies, blockchain technology offers a revolutionary solution by enabling the recording and sharing of production updates via an anonymous ledger. This approach ensures that all stakeholders have access to accurate, real-time data, establishing a reliable source of truth. Leveraging features such as timestamping, companies can effortlessly monitor the status and location of their products at any given moment. This capability effectively addresses critical issues such as counterfeit products, compliance breaches, delays, and wastage.[11]

Blockchain technology can contribute to the supply chain transparency by offering the following features:[12]

- Immutable record-keeping: Blockchain technology allows for the creation of a decentralised and immutable ledger that records transactions across the entire supply chain. Each transaction, such as the movement of goods from one party to another, is recorded as a block in the chain. Once recorded, these transactions cannot be altered or deleted, providing an unchangeable history of all interactions within the supply chain.

[11] https://onpassive.com/blog/role-of-blockchain-in-supply-chain-transparency-traceability/

[12] Cui, Y., Gaur, V. (2023). Supply Chain Transparency Using Blockchain: Benefits, Challenges, and Examples. In: Merkert, R., Hoberg, K. (eds) *Global Logistics and Supply Chain Strategies for the 2020s*. Springer, Cham. https://doi.org/10.1007/978-3-030-95764-3_18

- Enhanced traceability: With blockchain, stakeholders can trace the journey of products from their origin to the end consumer with unprecedented transparency. Each step of the supply chain, including sourcing of raw materials, manufacturing, distribution, and delivery, is recorded on the blockchain. This transparency enables consumers and businesses to verify the authenticity, quality, and ethical sourcing of products.
- Improved trust and accountability: Blockchain technology fosters trust among supply chain participants by providing a transparent and tamper-proof record of transactions. Since all parties have access to the same information, there is greater accountability throughout the supply chain. This helps in reducing disputes, resolving issues more efficiently, and building stronger relationships between stakeholders.
- Streamlined documentation processes: Traditional supply chain documentation processes involve multiple parties, manual paperwork, and complex verification procedures, leading to delays and inefficiencies. Blockchain streamlines these processes by digitising and automating documentation, such as invoices, contracts, and certificates of authenticity. Smart contracts, a feature of blockchain, can automatically execute predefined actions when certain conditions are met, further streamlining operations.
- Fraud prevention and risk mitigation: Blockchain technology mitigates the risk of fraud and counterfeiting by providing a secure and transparent record of product provenance. Counterfeit products can be quickly identified and removed from the supply chain, protecting consumers and preserving brand reputation. Additionally, blockchain's decentralised nature makes it resistant to cyberattacks and data tampering, enhancing the overall security of supply chain data.
- Compliance and regulatory requirements: Blockchain facilitates compliance with regulatory requirements and industry standards by providing auditable records of compliance throughout the supply chain. This can include adherence to environmental regulations, fair labour practices, and food safety standards. Blockchain enables real-time monitoring and reporting of compliance, reducing the administrative burden associated with regulatory compliance.
- Supply chain optimisation: By providing real-time visibility into supply chain operations, blockchain enables stakeholders to identify inefficiencies, optimise workflows, and reduce costs. Smart contracts can automate payment processes, trigger replenishment orders based on inventory levels, and optimise transportation routes, leading to greater operational efficiency and cost savings.

2.2.4 Drone surveillance

Employing drones for surveillance and security purposes can provide several benefits specific to the realm of inland ports:

Enhanced monitoring of port facilities: Drones equipped with cameras and sensors can provide real-time aerial surveillance of inland port facilities, including warehouses, storage yards, and transportation areas. This aerial perspective allows for comprehensive monitoring of large areas that may be challenging to cover with traditional surveillance methods. By regularly patrolling port facilities, drones can detect unauthorised access, monitor equipment, and identify potential security threats or safety hazards.

Improved perimeter security: Drones can patrol the perimeter of inland port facilities, providing continuous surveillance and monitoring of fences, gates, and entry points. With advanced imaging capabilities[13], drones can detect and respond to perimeter breaches or suspicious activities in real

[13] Zhao, R., Zhu, Z., Li, Y., Zhang, J., Zhang, X. (2021). Use a UAV System to Enhance Port Security in Unconstrained Environment. In: Zallio, M. (eds) *Advances in Human Factors in Robots, Drones and Unmanned Systems*. AHFE 2020. Advances in Intelligent Systems and Computing, vol 1210. Springer, Cham. https://doi.org/10.1007/978-3-030-51758-8_11

time, enabling security personnel to intervene promptly. This proactive approach to perimeter security helps prevent unauthorised access and intrusions, enhancing overall port security.[14]

Rapid response to incidents: In the event of security incidents or emergencies, drones can be deployed quickly to assess the situation and provide valuable situational awareness to security personnel and first responders. Drones can navigate through port facilities to gather real-time video footage and thermal imaging data, allowing authorities to assess the severity of the incident, identify potential hazards, and coordinate response efforts more effectively. This rapid response capability can help mitigate the impact of security incidents and improve overall emergency preparedness at inland ports.

Cost-effective surveillance solution: Compared to traditional surveillance methods such as manned patrols or stationary security cameras, drones offer a cost-effective solution for inland port surveillance. Drones can cover large areas efficiently, reducing the need for extensive manpower and infrastructure investments. Additionally, drones can be deployed on-demand, allowing port operators to allocate resources flexibly based on security needs and operational priorities.

Enhanced safety measures: In addition to security surveillance, drones can also contribute to safety measures at inland ports. By monitoring critical infrastructure, equipment, and operational processes, drones can identify potential safety hazards, such as spills, leaks, or structural damage, before they escalate into more significant incidents. This proactive safety monitoring helps prevent accidents, minimise downtime, and ensure the continuity of port operations.

Aerial photogrammetry: Drone photogrammetry represents an innovative approach to generating high-precision 3D models. Utilising this technique, a drone captures a multitude of aerial images from various vantage points, which are subsequently processed and modelled using specialised software. The resulting digital file can then be leveraged by different departments, such as the GIS department, to pinpoint new activities and users. This technology offers the capability to survey difficult-to-access or even inaccessible areas, yielding exceptionally accurate results swiftly. Moreover, it significantly reduces time requirements compared to traditional terrestrial topography methods, thereby conserving valuable resources.[15]

2.2.5 Data analytics for operational optimisation

In the ever-evolving landscape of port management, data analytics stands as a promising frontier yet to be fully explored. While the potential of leveraging big data analytics and machine learning algorithms for operational optimisation is recognised, its widespread adoption and integration into future port operations are still in their early stages. As ports continue to adapt to changing demands and technological advancements, the integration of data analytics holds the promise of unlocking new efficiencies and enhancing performance across various aspects of port management.

From the point of view of operational optimisation, the data analytics can be used in the following ways:

- Big data analytics: Ports generate vast amounts of data from various sources, including vessel tracking systems, cargo handling equipment, terminal operations, and environmental sensors. Big data analytics techniques are used to process and analyse this data to extract valuable insights and patterns. By aggregating and analysing data from disparate sources, port operators

[14] https://www.porttechnology.org/news/why-are-more-ports-using-drones/
[15] https://www.haropaport.com/en/news/drones-at-haropa-port-service

can gain a comprehensive understanding of port operations, identify trends, and make data-driven decisions.

- Machine learning algorithms: Machine learning algorithms can analyse historical and real-time operational data from the grain terminal to identify patterns, correlations, and anomalies. For instance, by analysing historical data on equipment performance and maintenance records, machine learning algorithms can predict potential equipment failures before they occur. This proactive maintenance approach helps prevent costly downtime and ensures uninterrupted operations at the grain terminal. Furthermore, machine learning algorithms can optimise berth scheduling at the grain terminal by analysing factors such as vessel arrival patterns, cargo volumes, and berth availability. By considering historical data on vessel arrivals and departures, as well as real-time information on current cargo volumes and berth availability, machine learning algorithms can generate optimal berth schedules that minimise congestion and maximise throughput at the terminal. Additionally, machine learning algorithms can forecast cargo volumes at the grain terminal by analysing historical trends and external factors such as weather conditions and economic indicators. By examining historical data on grain shipments and correlating it with factors such as weather patterns and market demand, machine learning algorithms can generate accurate forecasts of future cargo volumes. These forecasts enable terminal operators to anticipate fluctuations in demand and adjust their operations accordingly, ensuring efficient resource allocation and optimal inventory management at the grain terminal.
- Resource allocation optimisation: By analysing operational data, ports can optimise resource allocation across various activities, such as berth utilisation, cargo handling, and workforce management. For instance, data analytics can help identify bottlenecks in cargo flow, enabling ports to allocate resources more effectively to improve throughput and minimise delays. Similarly, predictive analytics can optimise maintenance schedules for equipment, reducing downtime and improving operational efficiency.
- Productivity improvement: Data analytics can help ports improve productivity by identifying inefficiencies and areas for improvement in port operations. For example, analysing vessel turnaround times can reveal opportunities to streamline processes and reduce idle time. Similarly, analysing container movements within the terminal can optimise storage and retrieval processes, leading to faster turnaround times and increased throughput.
- Opportunities for process optimisation: Data analytics enables ports to identify opportunities for process optimisation and performance improvement. By analysing operational data, ports can identify trends, patterns, and outliers that indicate areas for improvement. For instance, in case of sand and gravel terminals in inland ports, data analytics can help optimise resource allocation across various activities such as loading, unloading, and storage. By analysing historical data on cargo volumes, vessel arrivals, and equipment utilisation, terminals can identify peak demand periods and allocate resources accordingly. For example, data analytics can optimise the scheduling of loading equipment to match peak demand periods, reducing waiting times for vessels and improving overall terminal efficiency.

2.2.6 Digital twin technology

Digital twin technology was elaborated in Deliverable 3.2 in details. In a nutshell, Digital twin technology involves creating virtual replicas or representations of physical assets, systems, or processes. In the context of port infrastructure and operations, digital twins offer several benefits, such as:

- Simulation and visualisation: Digital twins enable port operators to simulate and visualise various aspects of port operations in a virtual environment.[16] This includes simulating vessel

[16] Neugebauer, J., Heilig, L. and Voß, S. (2024). Digital Twins in the Context of Seaports and Terminal Facilities. *Flexible Services Manufacturing Journal*. Available: https://doi.org/10.1007/s10696-023-09515-9

movements, cargo handling processes, and equipment utilisation. Digital replicas of the physical environment and processes allows port operators to assess different scenarios, identify bottlenecks, and optimise workflows for improved efficiency.

- Optimisation of port processes: Digital twins allow port operators to analyse and optimise port processes in real-time. By integrating data from sensors, IoT devices, and other sources, digital twins provide a comprehensive view of port operations. Port operators can use this data to identify inefficiencies, optimise resource allocation and workflows to improve productivity and reduce operational costs.
- Optimising operation energy consumption: Digital twin technology can be used for optimising energy consumption of cargo handling equipment. For example, the randomness of the arrival of container ships and container trucks, as well as the uncertainty of severe weather conditions and equipment failures, affect the operations of container yards. Additionally, an unbalanced load caused by an uneven distribution of, for example, automated stacking cranes (ASC) tasks, influenced the efficient utilisation of the capacity and therefore energy consumption of some ASCs unable to be effectively.[17] Thus, to further promote sustainable development, it is necessary to optimise container yard operations and improve equipment utilisation. Digital twins can be used to simulate various scenarios of ASC operations and help in modelling the optimised use patterns.
- Better decision-making: Digital twins provide port operators with actionable insights and data-driven decision-making tools. By visualising the impact of different decisions on port operations, operators can make informed decisions to improve performance and mitigate risks. Whether it's scheduling vessel arrivals, allocating berths, or managing cargo flows, digital twins help port operators make decisions that maximise efficiency and profitability.
- Risk management: Digital twins enable port operators to assess and mitigate risks more effectively. Thanks to their features, digital twins allow the operators to simulate various risk scenarios, such as weather events, equipment failures, or security breaches, which, in turn permits the operators to develop contingency plans and implement proactive measures to minimise disruptions and ensure continuity of operations. Additionally, digital twins can be designed in such way to facilitate regulatory compliance and enhance safety and security measures within the port areas.
- Performance improvement: Digital twins provide a platform for continuous performance monitoring and improvement. They also allow the tracking of pre-determined KPIs in real-time, thus allowing port operators to identify areas for improvement, set performance targets, and measure progress over time. This data-driven approach to performance management also enables port operators to optimise operations, enhance competitiveness, and deliver improved services to customers and stakeholders.

Digital twin technology stands at the forefront of revolutionising port operations, offering a sophisticated solution for enhancing efficiency and transparency. At its core, a digital twin is a virtual representation of a physical port environment, meticulously constructed using a combination of 2D and 3D data, georeferenced asset information, and panoramic photos.[18]

This digital replica serves as a powerful tool, providing stakeholders with a comprehensive and intuitive visual interface to monitor and manage port activities in real time. By leveraging advanced visualisation techniques, such as 3D modelling and geospatial mapping, the digital twin enables port operators to gain valuable insights into infrastructure, operations, and processes.

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[17] Yinping G., Daofang C., Chun-Hsien C. (2023). A digital twin-based approach for optimizing operation energy consumption at automated container terminals, *Journal of Cleaner Production*, Vol. 385. Available: https://doi.org/10.1016/j.jclepro.2022.135782.

[18] Hosken, J. (2023). Lean Methodology: Visuality is a link between the data and the people, *Port Technology,* 131, 31-34, Available: https://wpassets.porttechnology.org/wp-content/uploads/2023/05/09112916/PTI131_DIGITAL_v2.pdf

One of the key advantages of digital twin technology is its ability to facilitate better decision-making, risk management, and performance optimisation across various port functions. By integrating various data sources and processes into a unified platform, ports can optimise communication, enhance collaboration, and improve operational efficiency.

The implementation of a digital twin typically involves two primary phases. Firstly, port authorities create the digital replica of infrastructure data, leveraging existing datasets and technologies to generate an accurate and detailed representation of the port environment. Subsequently, various processes and workflows are integrated into the digital twin interface, enabling stakeholders to access critical information and perform tasks more efficiently.

In practice, digital twins have been instrumental in enhancing port operations across a range of activities, including berth planning, safety inspections, maintenance tasks, and communication with stakeholders. By providing a centralised platform for data visualisation and analysis, digital twins empower port operators to make informed decisions, optimise resource allocation, and improve overall performance.

Looking ahead, digital twin technology is poised to play an increasingly important role in shaping the future of port management. As ports continue to embrace digitalisation and adopt innovative technologies, digital twins will serve as invaluable tools for driving efficiency, safety, and sustainability in port operations.

2.2.7 Customs related platforms

Optimising customs and regulatory compliance processes is essential for efficient and seamless operations within inland ports. Digital collaboration between Customs authorities and port authorities/operators can improve the flow of goods across borders, especially where manual processes are impractical.[19] Electronic data and automated procedures can improve cooperation between different agencies as they allow smooth sharing of information. For example, technologies and practices such as digital platforms, integration of digital platforms with customs authorities, automation of compliance procedures and similar, can increase the efficiency of administrative work.

Digital platforms: The use of digital platforms for customs clearance processes enables electronic submission of documents by port operators, reducing the load of paper work. Digital platforms provide a centralised and standardised interface for submitting customs declarations, permits, and certificates, streamlining the clearance process for importers and exporters.[20]

Integration with customs authorities: Integrating digital platforms with customs authorities' systems allows for real-time exchange of information and data validation. Direct connection with customs authorities' databases allows port operators to verify the accuracy and completeness of submitted documentation, facilitating faster clearance and reducing the risk of errors or discrepancies.

Automation of compliance procedures: Automation technologies, such as robotic process automation (RPA) and artificial intelligence (AI), can automate routine compliance procedures, such as tariff classification, valuation, and rules of origin determination. Automation of repetitive tasks

[19] WCO & IAPH (2023). Guidelines on Cooperation between Customs and Port Authorities, Report. Available: https://www.wcoomd.org/-/media/wco/public/global/pdf/topics/facilitation/instruments-and-tools/tools/wco-iaph-guideline/wco-iaph-guidelines-on-cooperation-between-customs-and-port-authorities_en.pdf?la=en

[20] https://smartmaritimenetwork.com/2019/06/11/port-of-antwerp-unveils-digital-customs-platform/

allow port operators to speed up the clearance process, reduce manual errors, and increase regulatory compliance.[21]

Electronic Data Interchange (EDI): Implementing EDI systems makes unobstructed electronic communication and data exchange between port operators, customs authorities, and other stakeholders in the supply chain possible. It facilitates the transmission of standardised data formats, such as XML or EDIFACT, for customs declarations, invoices, and shipping documents, improving data accuracy and reducing processing times.[22]

Risk management tools: Data analytics and risk management tools can enhance customs compliance by identifying high-risk shipments and select them for random inspection by the authorities. Using the historical shipment data and applying risk assessment algorithms, port operators can identify potential issues in cargo declarations, notifying customs authorities to check and inspect such shipments.

Electronic seals and tracking technologies: The use of electronic seals and tracking technologies, such as RFID tags and GPS devices, enables real-time monitoring and tracking of cargo as it travels throughout the supply chain. These technologies can provide information on the location, condition, and security status of shipments, thus increasing the degree of regulatory compliance and improving security measures.

2.2.8 Position detection systems

Position Detection System (PDS) technology[23] is a specific kind of automated tracking systems based on the application of Radio Frequency Identification (RFID) tags and sensors, designed to monitor the real-time position and movement of targeted objects within port area or any other predefined area. Apart from the position of the targeted object, these systems can also determine and display other parameters, such as speed and direction of movement. Accurate and real-time information on the position of the movable object (trucks, cargo handling equipment and other vehicles, containers, etc.) allows port operators to have all needed inputs for better planning strategies related to yard space optimisation, reduction of traffic congestion, strengthening safety and increasing the overall efficiency of port operations.

Additionally, PDS technologies became very important in the domain of security, where real-time tracking of objects allow ports to perform quick identification of suspicious or non-authorised activities and take appropriate measures. Application of this technology can be very useful when identifying and locating containers with dangerous goods or stolen goods.

Benefits from the use PDS technology in ports encompass (but are not limited to) the following:

- Increased yard usage: Having full information on the available space and container arrangements in real-time enables port operators to perform movements of containers in a more efficient and safe manner.
- Pinpointing containers: Knowledge of the exact location of each container can significantly reduce the situations of lost or misplaced containers in ports.

[21] Jincheol L. (2023). Robotics Process Automation (RPA) And The Import/Export Customs Declaration Process, Global Trade and Customs Journal, 18:10, pp. 384-390, Available at: https://kluwerlawonline.com/journalarticle/Global+Trade+and+Customs+Journal/18.10/GTCJ2023042

[22] https://edicomgroup.com/blog/edi-as-a-tool-for-change-for-the-shipping-and-port-industries

[23] https://www.identecsolutions.com/news/smart-port-technology-implementing-pds

- Improved safety: Real-time tracking of cargo handling equipment, vehicles, and containers within the port area allows port operators to identify potential safety hazards before they occur, thus preventing related risks of accidents or injuries.
- Reduced time spent at the dock: accurate positioning data allows faster and easier container management and smoother operations.
- Faster cargo delivery: knowledge of the exact position of each container can help in reduction of cargo delivery delays from the yard to the gate.

2.2.9 *Automated terminals and smart ports*

Digitalisation is an indispensable and foundation pillar of any type of automation in ports. Digitalised ports and terminals can function perfectly without any automation, but automated ports and terminals cannot function without digitalisation which provides them with data, situational awareness, sensors that are constantly sending real-time information to automated equipment and/or their control centres and all other inputs necessary for their proper functioning.

Automation is one of the further digitalisation potentials, yet to be explored in inland ports. Automation, as a relatively new technology, found its prime application in container terminals due to the high value of cargo being shipped in containers, high costs of both vessels and container handling equipment and the consequent need to increase efficiency and shorten the waiting and loading/unloading time of container vessels in ports. In addition, the unitisation of cargo packaging (containers) and their standard dimensions, made the process of automation somewhat easier. Basically, any automated container terminal has three major groups of automated equipment: quay cranes (QC), automated guided vehicles (AGV) and automated stacking cranes (ASC). Quay cranes are not necessarily automated, but the trend of their automation is upwards, especially in the last decade. These cranes are increasingly becoming remotely operated, thus making them semi-automated. In case of, for example, unloading a container vessel, quay cranes lift containers from the vessel hold according to the previously received stowage plan and place it on an automated guided vehicle which, typically, follows the predetermined fixed route to a container yard, where a container is taken over by automated stacking crane which automatically stores a container in a predetermined storage (stacking yard) position. Most of the existing AGVs, as aforementioned, automatically follow a fixed route[24] from under the quay crane to the container yard and back. On the other hand, the development of 5G networks, sensor networks and Internet of Things, combined with Artificial Intelligence, enable the use of non-fixed paths for AGV movement. This can increase the operational efficiency as the AGVs using non-fixed paths can arrive at their destinations much faster than those using fixed (pre-determined) paths.

Automated Stacking Cranes (ASC) can automatically handle containers from both ends of the stacking (storage) yard, that is, from the quayside and from the gate side. On the quayside, containers can be transported and retrieved by AGVs while on the gate side they are usually transported and retrieved by chassis and trucks. Most stacking yards contain at least two ASC - one for quayside operations and the other for gate side operations. During low activity cycles, such as nighttime, ASCs usually reposition containers in light of the anticipated activity, such as an inbound ship to be loaded with a series of containers that are easier to retrieve sequentially.[25]

Container terminals are not the only type of terminals suitable for automation. For instance, bulk terminals are also convenient for automation thanks to the development of number of key

[24] Mohamed, K.W. and Khaldon, A.K. (2019), Connected Automated Guided Vehicles in a Smart Container Terminal. IOP Conference Series, Materials Science and Engineering, 533 012029, Available: https://ro.uow.edu.au/cgi/viewcontent.cgi?article=2113&context=dubaipapers

[25] Notteboom, T., Athanasios, P. and Rodrigue, J.P. (2022). *Port Economics, Management and Policy*, New York: Routledge. Available at: https://doi.org/10.4324/9780429318184

technologies, such as the long-distance materials detection, computer networks, automatic control, intelligent decision-making, grab anti-sway, path planning, video surveillance, and remote monitoring equipment.[26] All these technologies are implemented with the same ultimate objective as in container terminals – to increase efficiency and optimise the energy use. Typical automated bulk cargo handling equipment are the following:

- Automatic grab vessel unloaders,
- Automatic loading equipment,
- Automatic bucket stackers and reclaimers.

Automatic grab vessel unloaders for bulk cargo are equipped with scanning devices capable of scanning the vessel's holds and cargo in them. This is done in order to detect the location and distribution of holds (if there are multiple holds, which is typical for seagoing vessels and not so much for inland vessels and/or pushed barges). This can replace the manual setup of operations by the operator and allows for continuous vessel unloading, thus significantly increasing the operational efficiency and safety of operations. Automatic grab unloaders typically use laser ranging technology for automatic detection and identification of situational awareness, including the position of the vessel, location and dimensions of the hold(s), type and distribution of bulk cargo, etc. This scanning is performed constantly as both the vessel and cargo frequently move during unloading process.

When automatic loading equipment is concerned, such devices have the function of hold detection (position, dimensions, elevation, etc.), detection of cargo type and the flow of cargo, as well as video surveillance features. These functions assist in performing smooth and continuous operations, planning shipment paths automatically and effectively, reducing the dust, noise, and vibration at cargo transfer points. This type of equipment also uses various sensors to create situational awareness, detecting, for example, the relative position of the loading pipes against the vessel hold, or actual distribution of the cargo in the hold as it is being loaded.

Automatic bucket stackers and reclaimers are used on the land side, for the stacking of bulk cargo in piles on the open storage areas after the cargo is unloaded from a vessel, as well as for reclaiming it from the piles for the purpose of loading a vessel. This type of equipment is usually connected with the quayside loading/unloading equipment by the means of various bucker or belt conveyors. These devices also use a series of sensors to detect the shape and size of the piler where the cargo is stacked or reclaimed, as well as to position the buckets is such way to ensure optimal stacking or reclaiming, at the same time increase both safety and efficiency of operations.

Apart from container and dry bulk cargo terminals, practically all other types of terminals can be digitalised and, consequently, automatised.

Another untapped potential for inland ports is the area of smart ports. In order to avoid complicated definitions, the following definition is introduced: *smart ports are those ports which plan and perform their operational functions with the help of advanced digital and automation technologies for the purposes of optimisation of port operations and increase of efficiency, productivity and sustainability*. These advanced technologies include Big Data, Internet of Things, Data Analytics, Artificial Intelligence, Blockchain, automation, and others. Since smart ports tend to use advanced technologies for logistic optimisation and increase of efficiency, one of the major benefits of smart ports is their lower environmental footprint which can be significantly reduced thanks to these

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[26] Qifan, B., Xia, J., Zhaowei, W., (2019), Research and development of automatic bulk cargo equipment in modern ports: Part 1, *Port Technology International*, No. 5. Available: https://www.porttechnology.org/wp-content/uploads/2019/05/PT40-22.pdf

technologies. For this reason, smart ports are frequently referred to as smart and sustainable ports. A smart port is also data-centric, so it can produce, manage, and share related information. Furthermore, smart ports will play a key role as a data service provider in the data economy, thereby increasing their importance.[27]

All of the aforementioned technologies form the building blocks of smart ports.[28] More than 1000 individual 4.0 technologies were identified[29] and categorised technologies into four groups:[30]

- process technologies, encompassing, for example, robotics and additive manufacturing,
- interface technologies, such as IoT and visualisation,
- network technologies, involving cloud, blockchain and cybersecurity, among others,
- data-processing technologies supporting data analysis and data-driven decision-making, such as big data, machine learning and simulation.

In order to systematise various approaches to the building blocks of smart port technologies, the Study team proposed the classification as listed in the following table:

Table 2-3: Elements and technologies of smart ports

Smart port elements	Technology	Sustainability gains
Automated terminals and cargo handling	IoT, AGV, ASC, remote QC, simulation, 5G/6G networks, etc.	Optimised paths and routes with increased efficiency = reduction of emissions.
Port Community System	IoT, Blockchain, data analytics, cloud technology, AI.	Resource optimisation, waste management, reduced congestion and related emissions.
Traffic management systems (barge, rail, road)	Drones, automated cargo handling equipment, IoT, radar, River Information Services (RIS), etc.	Optimised movements and arrivals of vessels, trains, trucks and other vehicles, reduced emissions.
Smart port infrastructure	5G/6G networks, sensors, blockchain, AI, IoT, big data, digital twins, etc.	Renewable energy sources use, greening of port operations, energy management systems.
Smart safety and security	Augmented and virtual reality, IoT, OCR, CCTV, drones, big data, cloud technology, digital twins, etc.	Prevention of accidents, improved health of workers, regulation compliance, etc.

Source. Consortium.

On a journey to become smart and sustainable ports, inland ports are driven by, inter alia, the following drivers: [31]

- Operational efficiency: Increase of productivity through the use of smart technologies directly reduces costs and alleviate congestion of incoming vessels and land transport vehicles.
- Asset management: Another way of reducing operational costs can be achieved through the use of various sensors that measure, for example, structural health, corrosion levels, tensions,

[27] UNESCAP (2021), Smart Ports Development Policies in Asia and the Pacific, Report. Available: https://www.unescap.org/sites/default/d8files/event-documents/SmartPortDevelopment_Feb2021.pdf

[28] Heikkilä, M., Saarni, J., Saurama, A. (2022). Innovation in Smart Ports: Future Directions of Digitalization in Container Ports. Journal of Marine Science and Engineering, 10:1925. Available: https://doi.org/10.3390/jmse10121925

[29] Chiarello, F., Trivelli, L., Bonaccorsi, A., Fantoni, G. (2018). Extracting and mapping industry 4.0 technologies using Wikipedia. *Computers in Industry*, 100, pp.244–257. Available: https://10.1016/j.compind.2018.04.006

[30] Culot, G., Orzes, G., Sartor, M., Nassimbeni, G. (2020). The future of manufacturing: A Delphi-based scenario analysis on Industry 4.0. Technological Forecast and Social Change, 157. Available: https://doi.org/10.1016/j.techfore.2020.120092

[31] ADB (2020), Smart Ports in the Pacific, Asian Development Bank Report. Available: https://www.adb.org/sites/default/files/publication/646401/smarts-ports-pacific.pdf

vibrations, temperatures, friction of parts of equipment or infrastructure and suprastructure assets. Such sensors can be used for predictive maintenance and thus reduce the overall maintenance requirements.

- Business resilience: Various digital tools can be used to strengthen commercial business operations, to invest wisely in crisis management and business continuity, to be responsive to changes in port traffic and customer demands, and to provide robust service continuity (e.g., with cybersecurity) and staff capability and training.
- Safety and security: Various surveillance, monitoring and alarming technologies and systems are convenient to take over standard repetitive tasks, which typically results in operational safety increase.
- Energy efficiency: The use of smart technologies contributes to the increase of energy efficiency, which, in turn, directly leads to lower operational costs and reduced environmental footprint of port activities.

Further development of smart port technologies will likely bring new benefits for inland ports. Potential development steps could include (but not be limited to) the following:

- Improved connectivity: the use of existing smart port technologies will enable even more reliable real-time data exchange and seamless communication and coordination of work between various systems and stakeholders not only within the boundaries of ports themselves, but also with other stakeholders involved in supply chains.
- Advanced predictive analytics: models used in predictive analytics can detect anomalies in operational patterns, forecast operational trends, fluctuations in demand, anticipate maintenance requirements and optimise resource allocation accordingly. There is a vast number of uncertainties that can affect operational patterns and trends in ports[32] such as weather conditions, port dynamics, cargo variety, disruptions in on-haulage or pre-haulage of cargo and many others. This is where predictive analytics steps in and takes all these uncertainties into account when providing elements for data-driven decision-making.
- Advanced prescriptive analytics: this type of data analysis not only analyses the data generated by various port elements (equipment, vehicles, vessels, people, processes, cargo, etc.) and by their interactions, but it also prescribes (recommends) several optimal actions to achieve the desired objectives. One of the activities where prescriptive analytics can be of use is the dynamic berth scheduling.[33] Additionally, prescriptive analytics can be used in inventory management where it can assist in optimising stock levels, storage locations, and replenishment strategies. Using inputs such as demand forecasts, lead times, and supply chain constraints, prescriptive models can recommend optimal inventory policies to minimise stockouts, reduce holding costs, and improve service levels.
- Supply chain integration: both vertical and horizontal integration of supply chain actors, along with the globalisation of the trade revealed the need for closer integration between ports, shipping lines, logistic providers, and other stakeholders. Smart inland ports can use this opportunity to develop various digital tools, such as digital twins of the entire supply chain, and offer end-to-end visibility and seamless coordination across all elements of the supply chain, from manufacturing to distribution.
- Explainable Artificial Intelligence (XAI): Explainable AI (XAI) is artificial intelligence (AI) that is programmed to describe its purpose, rationale and decision-making process in a way that the average person can understand. XAI helps human users understand the reasoning behind AI

[32] Rao, A., Wang, H., & Gupta, C. (2024). Predictive Analysis for Optimizing Port Operations. ArXiv, abs/2401.14498. Available: https://doi.org/10.48550/arXiv.2401.14498

[33] Jauhar, S., Pratap, S., Kamble, S., Gupta, S., Belhadi, A. (2023). A Prescriptive Analytics Approach to Solve the Continuous Berth Allocation and Yard Assignment Problem using Integrated Carbon Emissions Policies. *Annals of Operations Research*. Available: https://doi.org/10.1007/s10479-023-05493-1 .

and machine learning (ML) algorithms to increase their trust.[34] This highly advanced form of Artificial Intelligence can be used in inland ports to provide transparency, interpretability, and accountability in AI-driven decision-making processes. For example, in predictive maintenance, XAI can provide explanations of various factors influencing maintenance-related or condition-related predictions, allowing personnel in charge to understand the reasoning behind every action recommended by AI. Furthermore, XAI can explain the rationale behind the measures that are recommended by AI for optimisation of maintenance measures and maximisation of the lifespan of the asset in question. In case of route optimisation for the movement of cargo within the port, XAI provide explanations of why certain schedules and routes are recommended, allowing the operators to make fully informed decisions. Another interesting example of the possible use of Explainable Artificial Intelligence can be seen in environmental monitoring applications. In this domain, XAI can provide explanations for environmental monitoring predictions, for example, for air quality forecasts, emissions tracking or similar. In this way operators would be able to understand certain processes related to the environmental pollution and to understand the measures proposed by AI well in advance, which, in turn, would enable them to take proactive risk mitigation measures and minimise environmental impact as much as possible.

2.2.10 Robotic vessels as a service – RoboVaaS concept

Although developed only to a prototype phase, the Robotic vessels as a service, or the RoboVaaS concept is a result of the Robotic Vessels as-a-Service (RoboVaaS) project which had a goal of using the relevant digitalisation and technological development for various port authority needs, offering a wide scope of services where autonomous survey vessels are of use for port authorities.[35]

RoboVaas concept involves small interconnected unmanned underwater and surface vessels. This concept can contribute to the cost reduction through the integration of new applications and service on a multiple-use platform. These autonomous vessels are equipped with multiple sensors, a reliable data transfer cloud network for over- and underwater communication, a monitoring station, and a real-time web-based user interface. A pre-registered user (e.g. container vessel) in a service area can request a service (e.g. anti-grounding for improved guidance in shallow waters) and will receive a live feed of processed data at the user interface.

The concept was developed five use cases, for five different types of services in ports:

- Anti-grounding,
- Environmental data collection,
- Ship hull inspection,
- Quay wall inspection, and
- Data mulling.

The concept was originally developed for seaports, but due to its high scalability it can be applied with very little or no adaptations at all in inland ports.

[34] https://www.techtarget.com/whatis/definition/explainable-AI-XAI

[35] Schneider, V.E., Delea, C., Oeffner, J., Sarpong, B., Burmeister, H.C. and Jahn, C. (2020) "Robotic service concepts for the port of tomorrow: Developed via a small-scale demonstration testbed", *European Navigation Conference (ENC)*, Dresden, Germany, 2020, pp. 1-8. Available: DOI:10.23919/ENC48637.2020.9317486

2.3 Further potentials for the greening of ports through digitalisation

In the Deliverables 3.2 and 3.5 the Study team has demonstrated that virtually all digital tools applied in inland ports across the globe have different degrees of potential to reduce the environmental footprint of port management and operations. Even the simplest web-based digital tool for reporting and invoicing can result in the direct or indirect reduction of environmental impact of port operations, if in nothing else then just in the reduction of paper use and energy consumption otherwise needed to distribute the documents in physical world.

The following section will provide more details on the further possibilities for the greening of port operations, through the sustainability dashboards in ports.

2.3.1 Sustainability dashboards in inland port operations

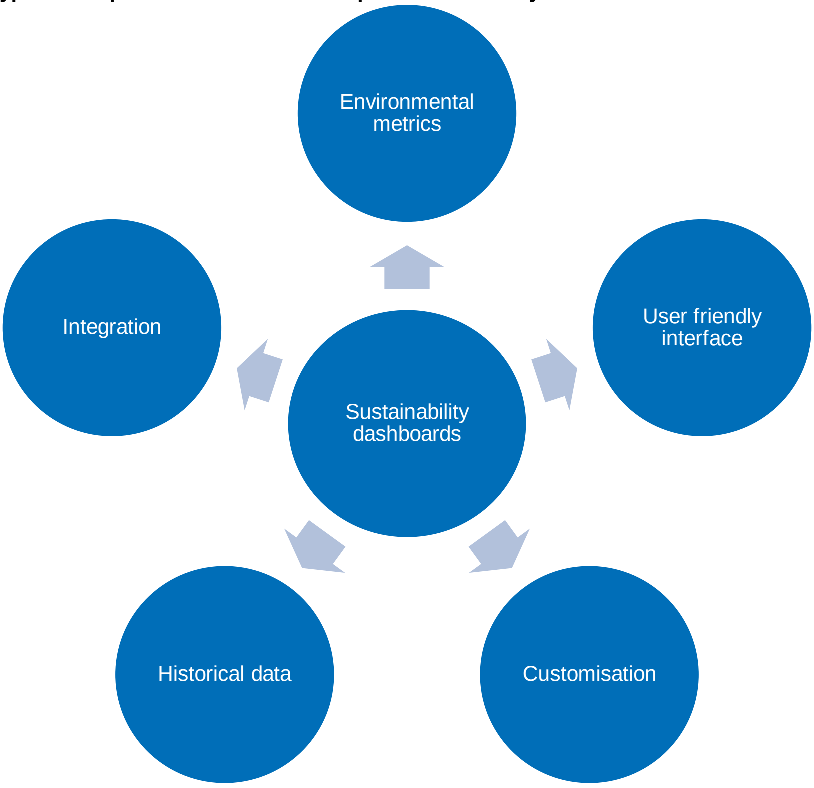
As one of the very convenient solutions for monitoring the overall environmental performance of inland ports, sustainability dashboards have emerged as powerful tools. Sustainability dashboards offer a comprehensive and transparent view of ports' environmental performance, aligning very well with the European Green Deal goals[36] of minimising environmental impact until 2050, optimising resource use, and demonstrating a general commitment to sustainable operations. Sustainability dashboards, apart from providing the clear and visible insight into the environmental footprint of port operations, can have a crucial guiding role for port operators on their path towards more environmentally responsible port management.

In a nutshell, a sustainability dashboard is a specially designed digital platform that provides real-time, data-driven insights into an inland port environmental footprint at predetermined "hot spots" or over the entire port area. This platform, or tool, collects data from various sources, such as IoT (or ordinary) sensors, monitoring systems, databases, and user inputs, to create a holistic view of the environmental performance of a port. Sustainability dashboards typically cover a wide range of sustainability-related metrics and KPIs, whereas the most common metrics are those measuring waste creation parameters, energy usage and air and water quality[37].

[36] https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52019DC0640

[37] Puig, M., Raptis, S., Wooldridge, C., Darbra, R.M. (2020), Performance trends of environmental management in European ports, *Marine Pollution Bulletin*, Vol. 160, Available: https://doi.org/10.1016/j.marpolbul.2020.111686.

Figure 2-4: Typical components and features of port sustainability dashboards



Source: Consortium

As indicated earlier, sustainability dashboards in inland ports can include a wide scope of environmental KPIs, such as energy consumption, greenhouse gas emissions, air and water quality, noise level, waste generation and, in recent years, the use of renewable energy sources. The data necessary for the KPI measurement is typically transmitted from IoT sensors deployed in strategic places throughout the port area, and, in certain cases, through manual measurements and inputs into the platform or software running the dashboard. The data on energy consumption can be aggregated from the so-called smart grids that are enabled by digitalisation. In this case, energy consumption can be monitored and adjusted in real-time, based on demand, which allows efficient energy use and opens possibilities to use renewable energy sources. Some sustainability dashboards can monitor the performance of renewable energy installations like solar panels or wind turbines, thus allowing their optimal operation and contribution to the overall energy mix.

In order to provide useful and intuitive interaction with users, sustainability dashboards have a user-friendly interface enabling users, such as port authorities, tenants, and other stakeholders, to have an easy access and understanding of the visualised data, so that they can interpret and understand the data in the right way. Such dashboards typically include interactive charts, graphs, and port layout or maps, so that the data is visually compelling and understood more easily.

Sustainability dashboards are, in most cases, customisable to fit the specific needs and goals of inland ports, their authorities and users. Since the sustainability dashboards are typically ran by port authorities, it is the port authority which sets which environmental KPIs will be monitored. Moreover, the thresholds for the environmental KPIs can be set either according to the regulatory requirements (where applicable) or according to the levels set by port authorities, as the case may be. In addition, the port authorities can configure alerts in cases when monitored KPIs exceed or fall below predefined values.

In addition to their capability to monitor the predetermined parameters in real-time, sustainability dashboards can store historical data for the same parameters, enabling users to track the development of those parameters over time. This is very useful for assessing the effectiveness of applied environmental initiatives or for identifying trends and patterns, as well as for data-driven decision making.[38]

Apart from displaying the predetermined environmental KPIs, sustainability dashboards can be integrated with other digital tools used in inland ports to display determined operational KPIs, so as to establish links between operational and environmental KPIs and determine their dependencies. This can help the authorities and operators in their decision-making processes and provide insights into the levels of sustainability of different operational technologies and practices applied in ports.

Sustainability dashboards can also be a tool for demonstrating accountability to stakeholders, regulatory bodies, and the public. Adding transparency about sustainability efforts can link inland ports closer to their host communities and raise positive awareness about ports and their role in sustainable development.

Data from sustainability dashboards can be fed into long-term strategic planning for ports, where ports can use the available data, trends and even predictions to set their sustainability goals as per relevant regulations or beyond such requirements. In this way, inland ports can allocate available and planned resources more effectively to reach their sustainability goals.

Below figure demonstrates the user interface of one sustainability dashboard encountered during the desk research. An interview with the developer confirmed that this dashboard was initially developed for seaports, but it can be easily adapted for the use in inland ports as well.

Figure 2-5: Sustainability dashboard by GISGRO

Source: www.gisgro.com

[38] Shields, J. F., & Shelleman J. M. (2020). SME sustainability dashboards: An aid to manage and report performance. *Journal of Small Business Strategy*, 30(2), 106-114. Available: https://core.ac.uk/download/pdf/328006276.pdf

2.4 Summary of digitalisation potentials for four different port systems

The Terms of Reference for the Study required, inter alia, the identification of “areas/processes that can be digitalised and how the existing digital tools and technologies can be improved in terms of processes and interoperability in four areas:

- Single port systems.
- EU inland port systems.
- EU inland ports and connecting EU seaports.
- Inland ports and stakeholders’ systems.”

In this report, in the context of operational differences and applied digital tools, the above four areas are considered as four categories of port systems:

- Single port systems: operations are not connected to external stakeholders, systems, or other ports; various digital tools should be connected and/or integrated between themselves, such as PCS with TOS, TOS with GOS, PCS with data analytics tools, TOS with predictive maintenance tools, etc.).
- EU inland port systems: inland ports along the same waterway or river basin, or inland ports in the same region, at the same time cooperating between themselves and competing for the same cargoes; they have the possibility of having their digital tools integrated, interoperable and connected, such as in the case of RiverPorts Planning and Information System - RPIS (known earlier as RhinePorts Information System)[39], which is the world’s first multiport community system for inland navigation.
- EU inland ports and connecting EU seaports: basically, these are the previous two systems together, with the addition of one or more connecting EU seaports. This connection can be physical, through direct railway, road or inland waterway connections, or logistic connection through regular shuttle/feeder services for cargoes provided by rail, road, or barge operators.
- Inland ports and stakeholders’ systems: this includes operational and digital connections of ports and terminals with external stakeholders (trucking companies, rail operators, freight forwarders, logistic operators, shippers, etc.) and their digital tools. The integration of digital tools among these stakeholders facilitates efficient coordination and information exchange throughout the supply chain.

Below table contains a selection of digital tools and technologies for inland ports identified in Deliverable 3.2, as well as technologies identified to have further digitalisation potential for inland ports in this report. In addition, the convenience of each tool for the use in one (or more) different categories of port systems is also marked in the table.

Table 2-4: Summary of digitalisation potentials for different categories of port systems

Digital technologies and tools	Categories of port systems			
	Single port systems	EU inland port systems	EU inland ports and connecting EU seaports	Inland ports and stakeholders’ systems
Port Community Systems	X	X		X
Predictive maintenance	X			

[39] https://rheinports.eu/en/

Digital technologies and tools	Categories of port systems Single port systems	EU inland port systems	EU inland ports and connecting EU seaports	Inland ports and stakeholders' systems
Supply chain visibility	X	X	X	X
Blockchain technology	X	X	X	X
Drone surveillance	X			
Data analytics	X	X	X	X
Digital twins	X	X	X	X
Customs related tools	X	X	X	X
Position detection systems	X	X	X	X
Automated terminals and smart ports	X	X	X	X
Robotic vessels	X			
Sustainability dashboards	X	X	X	X
Big data	X	X	X	X
Artificial intelligence	X	X	X	X
Internet of Things	X	X	X	X
AR & VR technologies	X			
Terminal Operating Systems	X			X
Gate operating systems	X			X
Asset management systems	X			
Multimodal booking platforms		X	X	X
Reporting applications	X	X	X	X

Source. Consortium.

Digital technologies, in an order as listed in the above table, are briefly discussed for applicability in different port systems in continuation:

Port Community Systems are convenient for single ports, multiple ports along the same inland waterway or a river basin, as well as for the connection with various digital platforms of different stakeholders. Good example of a multiport PCS can be found in RheinPorts, which have developed the RiverPort Planning and Information System (RPIS).[40]

Predictive maintenance platforms are typically developed for single ports as they are very concretely related to concrete equipment units in single ports. Nevertheless, it is not impossible that further development of this type of digital tools will not reveal predictive maintenance systems for multiple ports or terminals managed by single operators, in which case it may serve even as a much wider predictive maintenance management system.

The very nature of the supply chain visibility systems is such that they are made for the planning and management of the entire supply chains, thus also involving single ports, inland port systems, connecting seaports and different stakeholders (such as logistic providers, road hauliers, rail operators, etc.).

Blockchain technologies are very suitable for, for example, transfer of documents or financial transactions from one inland port to another, or between multiple inland ports, including the connecting seaports. When supply chain is monitored and cargo is transferred from one stage of a supply chain to another (say, from the manufactures warehouse to the road haulier that is to transport the goods to an inland port), the cargo can proceed from one stage to another only if a relevant part of the contract or transaction is completed, which is validated by relevant stakeholders having access to the relevant information in the blockchain. In other words, blockchain is a database for storing transactions that is shared among all the parties in a network. It serves as an encrypted ledger for information. The peer-2-peer network uses a consensus mechanism, which ensures that the transaction is valid before it is recorded to the ledger.[41] A participating stakeholder must validate a transaction by providing the same hash as the other stakeholders in the network. This hash is a specific and unique code that describes a message with information. The validated information is recorded on a block. A block can be compared to a container whereas everyone can see it from the outside, but only those with permission, a private key, can access the content. For these reasons, blockchain technologies are suitable for applications within all four categories of port systems.

Drone surveillance is convenient primarily for single ports mostly because of the limited range and autonomy of commercial drones. Aerial drones are used in ports for security and safety purposes, for aerial and visual inspection of determined areas, response to incidents, as well as for environmental monitoring. Even though some drones can be used to monitor areas beyond inland ports, such as access waterways, waterways between inland ports and connecting seaports, or even land access routes to inland ports, the Study team has the opinion that such surveillance would largely step out of the scope of activities of port operators and port authorities.

Data analytics platforms can be used in all four categories of port systems. In single port systems, data analytics platforms are used for data-driven decision-making on operation optimisation, processes such as berth scheduling or cargo handling, maintenance activities, etc. In EU inland port systems (multiple inland ports systems), data analytics can provide information on performance of individual ports of the system, and it can also identify trends and patterns between and across all ports in the system, thus allowing data-driven collaboration and coordination of work among individual ports in the system. For the port system consisting of EU inland ports and connecting EU seaports, data analytics can facilitate historical and/or real-time data sharing and traffic patterns

[40] https://rheinports.eu/en/

[41] Oude Weernink, M., van den Engh, W., Francisconi, M., Thorborg, F. (2017). The Blockchain Potentials for Port Logistics, Research Paper, Smart Port NL and Port of Rotterdam. Available at: https://smartport.nl/wp-content/uploads/2017/10/White-Paper-Blockchain.pdf

recognition between inland ports and connecting seaports, thus allowing operators and planners to identify potential delays or bottlenecks and optimise transportation routes.

Digital twins can also be used for all four categories of port systems. Potentials of digital twins for single ports have been discussed in previous section, as well as in the Deliverable 3.2. Digital twins can be extended over multiple inland ports along the same waterway, same river basin or the same region. In this way, a holistic view of the entire port system can be obtained, which, in turn, can contribute to coordination of activities or optimisation of cargo flows. In addition, in case of EU inland ports and connecting EU seaports, digital twins can facilitate seamless coordination and collaboration between these interconnected nodes, including the activities of, inter alia, vessel scheduling. Finally, digital twins can be used to model and integrate the systems of inland ports and various stakeholders' systems such as shipping lines, logistics providers, customs authorities, truckers, and rail operators.[42] The holistic view of the entire supply chain, or parts thereof, allow users and operators to share the necessary data in real time and make decisions in a collaborative way, thus increasing the efficiency and even sustainability of the entire supply chain or its determined parts.

Figure 2-6: Digital twin of an entire supply chain

Source. Yao, et.al.

Customs related platforms can be applied in all four categories of port systems. Although a separate authority is in charge of such tools, customs platforms can be tightly connected with multiple digital tools in single ports and across the supply chains for the purposes of real-time exchange of information and data validation, faster clearances, and risk mitigation.

Position detection systems found their application primarily in single ports, while they can be used in all four categories of port systems. While their application in single ports is rather evident and already explored in previous sections, position detection systems are very useful in systems that include both multiple inland ports and connecting seaports. Their use facilitates the monitoring of vessel movements along waterways, through locks and canals, and waiting areas prior to entrance in locks or seaports. This enables efficient navigation and safe passage between inland and seaports. When applied in systems that include inland ports and stakeholder systems, position

[42] Yao, H., Wang, D., Su, M., Qi, Y. (2021). Application of Digital Twins in Port System. *Journal of Physics: Conference Series*, 1846. Available: DOI:10.1088/1742-6596/1846/1/012008

detection systems can provide real-time tracking of both cargo (for example, containers) and vehicles transporting the cargo from one point to another.

Technologies that are enabling automated terminals and smart ports can be used in all four categories of port systems. Wide range of digital tools that are building blocks of automation can be integrated across multiple ports and even entire supply chains, while automated cargo handling equipment are more typical for single ports. It is very possible that, in the near future, automated land transport vehicles will bring the cargo directly from a manufacturer's warehouse under the crane in a port, for a direct loading onto a vessel. This will require a tremendous amount of planning and coordination work, and the digital tools are likely to provide good ground for such tasks.

Robotic vessels as a service concept needs to be distinguished from the concept of autonomous vessels which largely fall out of the scope of this Study. Robotic vessels of the so called RoboVaas concept[43] are primarily used for various tasks in single port systems, such as water quality inspection, hull inspections, quay wall inspections, etc.

Sustainability dashboards can be used in all port related systems. While these dashboards in single ports integrate the data from various sensors monitoring systems, databases, and user inputs from a single port, multiport sustainability dashboard collect the data from multiple ports and along the routes connecting various ports or nodes of the supply chains. Sustainability dashboards can provide visualisation of the sustainability (through relevant KPIs) across the entire route for selected cargo, where relevant data collection is performed. This enables users to have a holistic view of the environmental footprint of different supply chains.

In a very similar manner like in the case of data analytics, big data analytics platforms and tools are deployed to use huge amounts of data generated by various sensors and other sources throughout the port. The use of such data can provide insights into port performance, and it can contribute to the optimisation of operations and resource allocation, with the ultimate goal of the increase of the overall productivity and efficiency. Similar use of data in multiple port systems (including connecting seaports can play a crucial role in analysing data from the entire logistics chain, spanning from inland terminals to seaport terminals, for the purposes of the improvement of the overall system efficiency. When data sources include various stakeholders' systems, such as those of logistic operators, shipping companies, truckers and rail operators, integrated analysis of all that vast amount of data can be done with the goal of supply chain visibility, improving collaboration in multimodal transportation chains, foster decision-making, etc.

Artificial intelligence is one of the most promising tools in further digitalisation and automation of inland ports and it can be applied in all types of port systems and beyond. In single port systems, AI technology can perform data analysis, predict arrivals of truck, trains and vessels, predict traffic demands or peak traffic, assist in resource allocation, assist in predictive maintenance tasks, etc. In multiple ports systems (including the connecting seaports), AI can assist in predictive and prescriptive analytics for cargo demand forecasting along the waterway or region where ports belonging to the system are positioned, route optimisation. In addition, AI-based predictive modelling can optimise intermodal logistics operations and improve container terminal efficiency. When stakeholders' systems are integrated in the fourth category of port systems, AI-driven analytics can facilitate information sharing, optimise cargo routing and handling and detect anomalies which can be very useful from the safety aspects. AI can have a significant role in enabling sustainable and resilient supply chains. A resilient supply chain provides visibility,

[43] Schneider, V.E., Delea, C., Oeffner, J., Sarpong, B., Burmeister, H.C. and Jahn, C. (2020) "Robotic service concepts for the port of tomorrow: Developed via a small-scale demonstration testbed", *European Navigation Conference (ENC)*, Dresden, Germany, 2020, pp. 1-8. Available: DOI:10.23919/ENC48637.2020.9317486

predictability, and flexibility with the addition of supply chain AI solutions and applications that make recommendations based on dynamically changing, real-time data.[44] These supply chains are called AI-driven supply chains. AI is useful in identifying the impact of emerging logistical issues and taking proactive and timely actions based on likely scenarios. Transportation routes can be AI-optimised for desired objectives, such as cost, delivery times, or risk, and can recommend alternative routes as new conditions emerge. Last, but not least, supply chain operations, starting from sourcing and contract manufacturing all the way to warehousing and transportation, can have a significant carbon footprint. Measuring, monitoring, and assessing the environmental impact of supply chain operations and accordingly identifying initiatives to improve their sustainability, is a role that AI is perfectly suited for.

Internet of Things is another advanced technology that found its application in all port related systems. In single port systems IoT sensors and devices are deployed throughout the port to monitor various parameters, such as cargo and vehicle movements, berth occupancy, cargo handling equipment condition, environmental parameters, etc. These sensors collect and transmit data in real-time, and other tools can take over and analyse the data or use them to make or propose decisions, provide inputs for data driven decision-making or simply display them for visualisation through convenient KPIs so that operators can take various actions. In case of multiple port systems, IoT can facilitate interoperability and data exchange between different port facilities.[45] When port systems consisting of EU inland ports and connecting EU seaports, as well as those involving stakeholders' systems are concerned, IoT enabled platforms, systems and tools can improve supply chain visibility, contribute to vessel scheduling and berthing arrangements and facilitate efficient transfer of cargo between different transport modes.

Augmented Reality (AR) and Virtual Reality (VR) tools are mostly applied in single port systems, due to the very nature of such technologies. Single port systems typically have a more defined and contained operational environment compared to multi-port systems or systems involving multiple stakeholders. AR and VR technologies are very conveniently designed for creating immersive digital replicas or simulations of concrete elements of port infrastructure or suprastructure, allowing users to visualise and interact with various elements such as terminals, vessels, cargo, and equipment in a virtual environment.

Terminal operating systems (TOS) are typically designed software tools aimed at assisting the operators to manage and operate cargo terminals in a port. They usually contain simulated elements of terminal infrastructure and equipment, layout of the terminal, ship-to-shore transfer areas, handling areas, internal roads and rails, etc, thus being much more suitable for single port systems. TOS are designed to manage and optimise terminal operations, including vessel berthing, cargo handling, storage, and the use of equipment within a single (specific) port environment. The concentrated scope of operations in single ports aligns well with the functionalities offered by TOS. Therefore, their use in multiport systems is limited, if not negligible. However, TOS can be connected with systems of external stakeholders, such as shipping lines, road or rail operators, in order to transmit and receive information on cargo in real-time and/or well in advance, which can simplify the planning process and coordination of arrivals and departures of both land vehicles and vessels.

Gate operating systems (GOS) consists of software and hardware, specifically designed to control the access to the port area. It typically consists of a software having the tasks of scheduling,

[44] https://c3.ai/blog/the-power-of-ai-in-supply-chain-management-for-increased-resilience-and-growth/

[45] Giménez, P., Llop, M., Olivares, E., Palau, C., Montesinos, M., Llorente, M. (2020). Interoperability of IoT platforms in the port sector. *Proceedings of 8th Transport Research Arena TRA 2020*, April 27-30, 2020, Helsinki, Finland. Available: https://www.researchgate.net/publication/339883632_Interoperability_of_IoT_platforms_in_the_port_sector

coordinating, and managing the activities at the port gate, automated gates with various sensors and scanners, Radio Frequency Identification (RFID) or license recognition system, and various physical access control devices. GOS are usually connected with single port systems digital tools, such as Terminal operating systems (TOS) for the purposes of facilitation of data exchange and efficiency of operations. Gate operating systems can also be connected to external stakeholders' systems, such as, trucking management systems, freight forwarding systems or various digital tools of logistic providers. Inland ports can use Electronic Data Interchange (EDI) systems to exchange electronic documents, such as shipping manifests, delivery orders, and customs declarations, with trucking companies and other external stakeholders. Inland ports can also offer Application Programming Interface (API) access, thus permitting trucking companies to integrate their digital tools directly with the port's GOS. This enables easy and fast data exchange and automation of processes such as gate appointments, pre-arrival notifications, and electronic document submission.

Asset management systems are specific tools designed primarily for of single port authorities and terminal operators for efficiently managing and maintaining their assets, cush as infrastructure, cargo handling equipment and other facilities. Asset management systems can range from a basic digital record of a port's assets to an overall IoT-based asset management tools that enable proactive tracking and monitoring of the port's equipment, structures, and infrastructure. These features are very useful for the proactive scheduling of maintenance tasks or rent of certain assets, such as warehouses, equipment units, etc. Therefore, these systems are mostly used in single port systems.

Multimodal booking platforms are digital systems that are mostly not direct port digital tools. They are designed to optimise and coordinate cargo across different transport modes. These platforms offer features such as cargo or vehicle/vessel booking, management of processes and tracking of cargo as it travels from its origin to its destination, so that the shippers can choose the best transport options based on cost, transit time, environmental footprint, or any other specific requirement. For these reasons, these platforms have found their place in all non-single port systems.

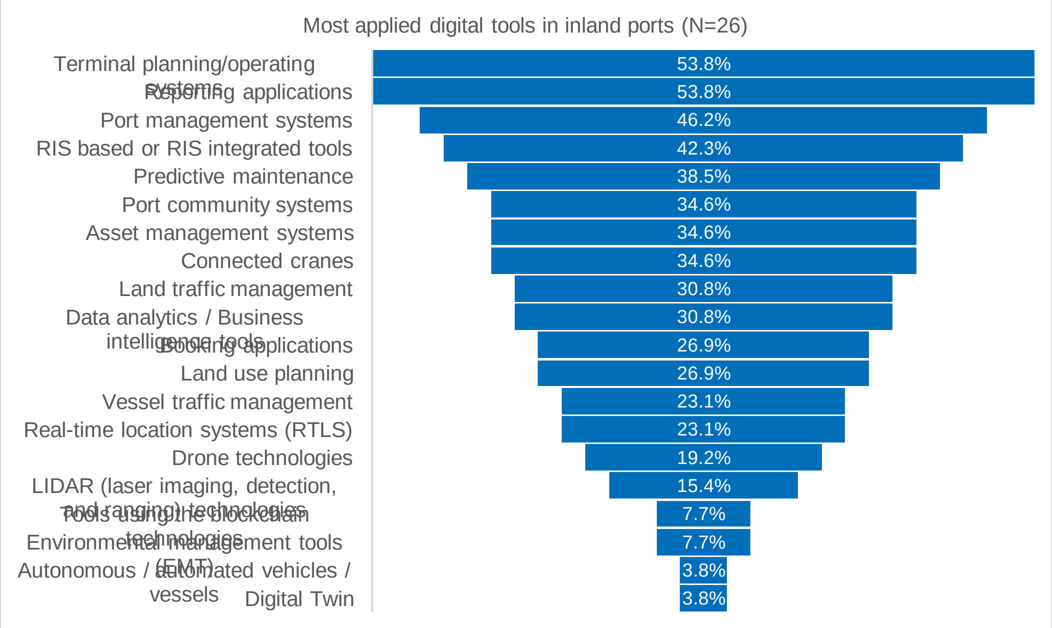
Reporting applications are specific software solutions used for the collection, analysis, and visualisation of data generated within a port or terminal. They are used to provide relevant information to the users, allowing them to make informed decisions, monitor different processes, and comply with various regulatory requirements. Therefore, their benefit for single ports is straightforward and clear. For multiple ports systems, reporting applications can combine information from different ports and thus provide data on regional cargo flows or inputs necessary for strategic planning, infrastructure investment decisions and collaborative initiatives. In multiport systems including EU seaports, reporting applications can support cross-port data exchange and collaboration, which can help in identifying bottlenecks or different trends of cargo movements. This integration enables better coordination and synchronised decision making between the ports in the system. Finally, in systems involving external stakeholders, reporting applications can be used for the purposes of coordination, monitoring of cargo movements, and collaborative decision making.

3 Optimisation of existing processes in inland ports

3.1 Optimisation of operational processes through digitalisation

Inland ports have recognised the importance and benefits of digitalisation for the increase of productivity, efficiency, customer satisfaction and even environmental footprint reduction. This was demonstrated through the results of the first Survey conducted amongst inland ports in the summer of 2023.[46]

Figure 3-1: Applied digital tools in inland ports – survey results



Source: Consortium

Through the use of advanced technologies and innovative solutions, digitalisation enables the optimisation of operational processes in ports, automation of routine and repetitive tasks and data-driven and data-assisted decision making.

Previous sections have brought additional insights into further digitalisation potentials with digital tools and technologies that have only started to gain momentum in port management and operations, while Deliverable 3.2 elaborated on the wide array of digital tools that are used in inland ports.

In view of optimisation of operational processes, digitalisation can assist in the following core processes in ports:

- Traffic management, such as berth scheduling, vehicle appointment processes, gate access, internal road and rail traffic processes, traffic of cargo handling equipment, etc.

[46] Ecorys, et.al. (2023). Inventory of port cooperation and collaboration systems, digital tools and applications and assessing their effect on greening and economic sustainability objectives, Deliverable D 3.2 of the *Study on Enabling Sustainable Management and Development of Inland Ports*, funded by the European Commission.

- Cargo handling processes, such as ship-to-shore loading/unloading, movement of cargo between the quay and the handling and storage areas.
- Infrastructure, suprastructure and equipment management.
- Logistic and value-added processes.
- Administrative tasks.

The most important aspect of traffic management in ports is always the berth scheduling, especially due to the fact that such facilities are limited and may be very scarce at certain terminals. Some terminals can have one berth only, capable of serving one vessel at the time (excluding specific and exceptional cases when two or more barges can be berthed one next to other, sideways, and when a crane, depending on its reach and lifting capacity at maximum reach, can simultaneously load/unload more than one barge). Digitalisation facilitates dynamic berth scheduling systems that take into account the dynamics of vessel arrivals, cargo types and terminal or berth capacity in real time. Thanks to automated scheduling algorithms, berth utilisation can be optimised, thus minimising vessel waiting times and reducing queueing and congestion. In addition, resources determining berth capacity can be efficiently allocated, in accordance with the dynamic operational conditions at given moments. Such optimisation can result in shorter vessel turnaround time and maximised berth throughput. As a final result, optimised movements mean less fuel consumption and, consequently, reduced emissions of pollutants.

Another important aspect of intra-port traffic management are vehicle appointment processes. Port are increasingly using digital appointment systems that are allowing trucking companies and other relevant stakeholders to schedule appointments for cargo pickups and deliveries from/to ports in advance. Those systems are fed with information on current status of traffic parameters through various sources, such as IoT sensors, CCTV cameras, RFID and other location devices, thanks to which they are able to provide a holistic picture of the facilities and traffic situation, thus enabling either automatic vessel appointments or user-selected time slots based on the available capacity at a given moment. In busier ports, such systems provide visibility into availability of time slots, enabling users to efficiently book appointments which, in turn, can minimise congestion at the gates, reduce queueing of trucks and optimise overall road traffic flows within the port. Such systems are usually connected with the Gate operating systems that automate the process of entry and exit of vehicles at the port gates.

Furthermore, digitalisation can assist in real-time monitoring and optimisation of internal road and rail traffic within port or terminal boundaries. Digitalised traffic management systems also use various technologies to collect both static and dynamic (real-time) data, and based on such data, identify congestion hotspots, and reroute traffic in order to avoid bottlenecks, thus optimising the internal traffic flows and increasing the overall efficiency and safety. In a very similar way, digitalised control systems can also optimise the movements of cargo handling equipment, such as cranes, reach stackers, forklifts, tractor trailers, straddle carriers and AGVs. These control systems can automate the routing vehicles and handling equipment, prioritise tasks on the basis of the cargo handling requirements in a given time, and optimise the utilisation of cargo handling equipment in such way to minimise idle times and maximise productivity. Such optimisation can also provide good coordination between cargo handling operations and traffic management processes.

In cargo handling processes, one operation stands out as the most notable and most critical one – ship-to-shore loading and unloading operation. In this operation, shore cranes are playing the major role, and their proper, safe, and efficient utilisation is a key to efficient operations. Digitalisation can help optimise crane operations as well. For example, in the case of bulk cargo handling, digitalisation can enable real-time monitoring of crane movements and crane position, using GPS or position sensors installed on the crane. Thanks to the integration of the data on movements and position with terminal operating systems, operators can track the exact location of the crane, and optimise their positioning on the basis of berthing schedules and cargo storage availability, while minimising idle time between different tasks. Digital control system enable precise control of grab crane movements, including hoisting, lowering, slewing, luffing and transversal travel. Optimisation of these movements is done typically through automation thanks to the digitalisation enabled data processing, on the basis of input parameters such as cargo type, weight, stowage factor and loading/unloading position in the ship holds or on the handling area behind the quay. Load sensors enable constant monitoring of the cargo grabbed in a grab, ensuring that cranes are not overloaded. Other sensors can help reducing or eliminating swaying movements of a grab, thanks to anti-sway devices run by complex algorithms that use feedback from sensors to detect and counteract unwanted movements, ensuring smooth and precise positioning of the cargo and safer crane handling. Minimisation of unwanted movements improves the overall safety, reduces the risk of damages, and increases overall efficiency of operations. Last but not least, digitalisation enables the implementation of collision avoidance systems and path planning algorithms to optimise crane movements and collisions with vessel parts, other cranes, or other handling equipment, and even humans. These systems can identify potential collision risks or proximity of other objects and, thanks to this feature, either dynamically adjust crane movements or trigger a warning to the operator, usually coupled with emergency stop functions. This type of optimisation of the cargo handling process can improve safety, reduce downtime caused by accidents and increase throughput by ensuring uninterrupted crane operations.

Infrastructure, suprastructure and equipment (or asset) management is another core port activity very convenient for optimisation through digitalisation. All three major types of assets (infrastructure, suprastructure and equipment) are managed from three different but connected aspects: maintenance, utilisation, and leasing (to third parties). Maintenance activities cover regular and predictive maintenance, as well as capital or investing maintenance or major overhauls, including reconstructions. Utilisation activities are related to operational use of assets either directly (by port authorities) or indirectly, by independent port or terminal operators. In the latter case, those activities are closely related to the leasing activities. Leasing activities include the lease of infrastructure, suprastructure and/or equipment to third parties such as concessionaires or port/terminal operators, on the basis of operational authorisation, lease contracts or concession agreements.

From the maintenance aspect, digitalisation can optimise regular, predictive, or capital maintenance. For both capital and regular maintenance, related digital platforms can assist in scheduling and execution of routine maintenance tasks for all types of assets by tracking maintenance schedules, recording the maintenance activities and generating alerts for the scheduled tasks. Moreover, digital asset management systems can track the budgets for capital maintenance activities, manage project implementation and timelines and coordinate resources to timely implement all planned activities of capital maintenance or major overhauls. All these activities contribute to the maintenance of assets in optimal conditions. Predictive maintenance is the most advanced digital strategy for maintenance, and it has been discussed earlier in this report. In a nutshell, predictive maintenance is based on the use of various sensors that collect the data on the current or predicted status of assets and their critical parts. In addition to that, data analytics tools suggest maintenance or replacement of parts based on the current health of assets and their monitored parts. This is the optimal maintenance strategy from the point of view of planning and costs.

Utilisation of assets can be viewed from two sides: direct operational use of assets by the owner/manager (typically a port authority, when a port authority also performs operating functions in a port), or indirect use by independent port or terminal operators. In the latter case, utilisation of assets is tightly related to the leasing activities. In both cases, digital tools can optimise the use of assets by tracking the defined usage metrics, such as throughput volumes, occupancy rates, equipment uptime or downtime, equipment productivity under different scenarios and conditions. Having insights into the usage metrics, operators can make data-driven decisions and maximise productivity and efficiency of assets. Moreover, if data analytics tools are involved, especially more advanced ones, like predictive and prescriptive analytics, operators can optimise their usage strategies even better.

Digital tools can also optimise the lease or concession agreements implementation and monitoring, thus ensuring compliance with lease obligations. Leases or concession agreements are typically accompanied by a set of agreed KPIs needed to be reached throughout the duration of the lease or concession period. In this view, digital tools can provide the tenants (concessionaires, lessees) the simple and easy way to track their own performance and to perform payments accordingly. Similarly, tailored digital tools can provide an easy and straightforward way to asset owners (concession givers or lessors, in both cases they are typically a port authority) to keep track of operators' performance and optimise revenue generation from leased assets.

Logistic processes in ports greatly vary from port to port. Smaller and more dedicated ports offer no or very limited logistic and value-added services to cargo and they perform only basic loading/unloading and storage functions. Smaller proactive ports, medium ports, and large ports, offer a wide range of logistic and value-added services to cargo, such as:

- inventory,
- groupage,
- labelling,
- packing,
- ordering,
- picking,
- bar coding,
- return (empties),
- customising,
- breaking shipments,
- de-waxing (cars),
- washing (cars),
- goods inspections,
- quality control,
- weighing services,
- distribution services.

Digitalisation can be applied to virtually all of the above services to a full or to a certain extent. For example, in inventory management, digitalisation can provide real-time visibility into stock levels, locations and movements of cargo within the port or a terminal. In addition to this, automated inventory tracking and barcode scanning can greatly facilitate inventory management processes, improve the accuracy of inventory records, and reduce human errors. In case of groupage, digital platforms can help in consolidating small shipments into larger groups, thus optimising container utilisation. For labelling, highly digitalised automated systems can generate and print shipping labels according to the regulatory requirements. Digital packing solutions can enable automated packing according to the dimensions and characteristics of cargo. When applied to container stuffing, advanced packing algorithms can optimise the stuffing density and minimise waste of space, thus reducing the cost of stuffing and maximising the volume utilisation. Digital order management systems typically include electronic placement and processing of orders, as well as tracking. They are usually integrated with inventory and other logistics systems, thus facilitating the visibility of orders and status updates. Digital picking systems can optimise the selection and retrieval of cargo parcels from warehouse or storage areas. Return of empty containers can be an integral part of the tasks performed by Terminal operating systems or standalone digital solutions or modules. Digital systems for deconsolidation or braking of shipments optimise the disassembly or separation of larger shipments into smaller units for the purposes of further distribution or individual sale. Advanced algorithms used in such systems can optimise the separation of shipments on the basis of destination, weight, volume, or any other handling requirements.

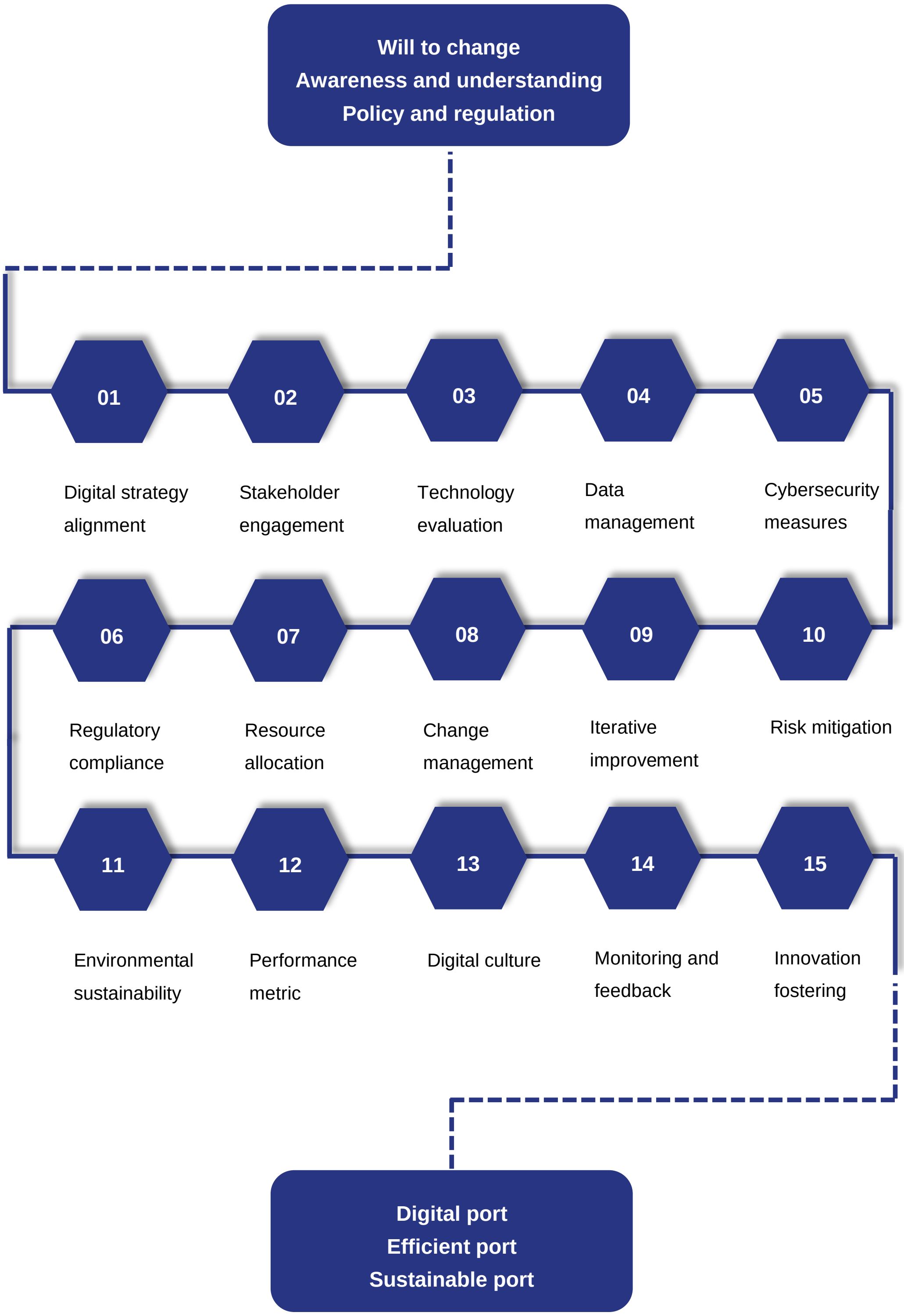
All other services can be digitalised on the basis of their own features and specificities. Digitalisation can optimise all these logistic processes in ports through automatisation of various tasks or by assisting human employees with various digital tools and devices. Whichever technologies are used digitalisation can optimise logistic processes by task automation, improvement of visibility, and overall increase of efficiency in the wide array of services. Application of digitalisation can therefore make the operations easier, reduce costs and deliver services of significantly higher quality to various stakeholders and customers.

Inland ports can optimise administrative tasks and paperwork by adopting novel technologies such as digital document management systems, electronic or web-based invoicing platforms, digital cargo declarations to various authorities, online permit applications, etc. Digitalisation of routine administrative processes and paperwork can significantly reduce the burden on employees, increase their efficiency and reduce processing times and related costs. Digitalised administration can also optimise communication, document exchange and collaboration between different port stakeholders, thus enhancing transparency and accountability in administrative tasks in inland ports.

3.2 Optimisation of digitalisation processes

Optimisation of processes in ports does not necessarily cover only standard operational processes in ports, like traffic management, infrastructure management, cargo handling activities and so on. Since the digitalisation itself is also a process, it is also subject to optimisation. The Study team proposes the following 15-steps method for the optimisation of digitalisation processes in inland ports, illustrated in the following figure:

Figure 3-2: Steps for optimised digitalisation process in inland ports



Source: Consortium

In order to optimise the digitalisation process in an inland port, its port authority first needs to have the willingness to change.[47] This willingness can be of dual nature: self-generated, as a result of awareness and understanding of the possibilities, benefits and needs of digitalisation, and induced willingness, in which case it turns into a compliance, as a result of the need to comply with the

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[47] Solmaz, M. S. (2021). Digital Business Transformation in Ports: IoT Applications in Port Management and Strategies. In K. Sandhu (Ed.), *Emerging Challenges, Solutions, and Best Practices for Digital Enterprise Transformation*, (pp. 221-240). IGI Global. Available: https://doi.org/10.4018/978-1-7998-8587-0.ch012

relevant policies and regulations. In both cases, a port authority would want to undertake the process of digitalisation in an optimal manner, from the view of time, efforts and needed resources.

The first step in optimised digitalisation process is the digitalisation strategy alignment, which involves the drafting of the digitalisation strategy itself, and its alignment with the business objectives of the port. This alignment includes the definition of specific goals, where the digitalisation efforts need to be directed. These goals may include improvement of operational efficiency, optimisation of maintenance strategies, higher quality services, combating congestion, or reduction of environmental footprint of port activities. An optimised digitalisation process needs to be accompanied by thorough understanding of how digital tools and technologies can support the port's strategic objectives and development goals.

Next step is stakeholder engagement. Inclusion of various relevant stakeholders throughout the digitalisation process is a very important step as it may contribute to the identification of priorities, addressing of concerns and clarification of stakeholders' needs. Stakeholders typically include port authorities, terminal operators, shipping lines, customs, cargo owners, local communities, environmental organisations, and others. Their collaboration and input may be of crucial importance during the planning process.

Technology evaluation of available digital technologies and tools is an important step prior to making investment decisions. Aspects that are typically considered during the evaluation of the most suitable digital tools for specific goals and purposes are scalability, compatibility with legacy systems, data security measures, possibilities of integration and interoperability with existing digital tools, if any.

Maximisation of the value of digitalisation process is in direct function of the effective data management. In order to maximise this value, ports have to optimise the data collection, storage, and processing methods from the point of view of data quality, accessibility, and security.[48] This means that ports need to implement robust data management processes and systems designed to support efficient decision making on the basis of accurate and timely data. In view of data collection, this encompasses the definition of clear data collection protocols and standards, implementation of automated data collection mechanisms (IoT sensors, RFID tags, GPS tracking systems, etc.) whenever and wherever possible, and regular monitoring of data quality and integrity. In terms of data storage, ports must ensure that secure and scalable data storage (and backup) is established, so as to accommodate the volume and variety of data generated in the port. These storage areas can be either cloud based or on-premises, whereas appropriate security measures must be established. Data processing methods include data normalisation, cleansing and enrichment to ensure the usability, accuracy, consistency, and relevance of data for analysis. Data governance, security and privacy are also important elements of effective data management. Naturally, the data analytics also represents a crucial element of data management, increasing the value of both data and digitalisation as an entire process.

Robust cybersecurity measures in ports need to be absolute priority as they are critical for safeguarding port operations and generated data from potential cyber threats. This involves proactive identification and addressing of vulnerabilities in ports' digital systems and networks, as well as implementation of measures such as firewalls, encryption, regular security audits, etc.

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[48] Herodotou, H., Aslam, S., Holm, H., Theodossiou, S. (2021). Big Maritime Data Management. In: Lind, M., Michaelides, M., Ward, R., T. Watson, R. (eds) *Maritime Informatics*. Progress in IS. Springer, Cham. Available: https://doi.org/10.1007/978-3-030-50892-0_19

An optimised digitalisation process also involves regulatory compliance from various aspects of port-related activities, such as data privacy, environmental protection, customs regulation, and others.[49]

Efficient resource allocation, in view of financial and human resources, is of the highest priority for successful digitalisation processes in ports. For this reason, ports should optimise their resources in such way to have clear budgets and priority projects aligned with their strategic objectives. Additionally, ports should make sure that they have skilled personnel trained and capable of implementing their digitalisation projects. Only careful planning and optimised resource management can maximise the return of investment in digitalisation efforts.

Digitalisation of ports is a significant effort and requires thorough and effective change management strategies in order to reduce disruption and ensure the acceptance and support from the employees. This means that ports need to communicate with their own employees effectively and to provide training and support, while at the same time addressing concerns and resistance to change. Only in this way the digital transformation can be performed in a smooth and efficient manner.[50]

Since digitalisation is not a finite process, ports should evaluate and improve their digitalisation efforts continuously. Continuity of evaluations and improvements, even through trial-and-error cases, is essential for the successful iterative improvement. By applying such practices, ports can ensure that their digitalisation efforts are always aligned with the dynamic business needs and objectives.[51] When improvement areas and optimisation possibilities are identified through evaluations, ports can intervene and take necessary actions through informed decisions. Apart from information gained from evaluation processes, ports can capitalise from feedback from stakeholders and data analysis.

Risk mitigation involves proactive identification of risks associated with digitalisation, and implementation of mitigation measures. This encompasses detailed risk assessments, development of mitigation plans and measures and regular controls to address potential threats. Risks associated with digitalisation can be cybersecurity threats, data breaches, failures in technology, failures to comply with regulation, disruptions in operation, etc.[52]

Environmental sustainability may not be the prime driver of digitalisation processes in ports, but it is certainly an important one. Driven by own environmental protection awareness, social responsibility and relevant policies and regulation dealing with transport-generated emissions, inland ports tend to minimise the environmental footprint of port operations. Digitalisation offers a variety of possibilities for ports to contribute to the ultimate goal of reducing their environmental impact.[53] For this reason, ports frequently integrate environmental sustainability in their digitalisation processes. In view of digital tools, ports can optimise their performance by using various sensors for emission and noise detecting and monitoring, digital platforms for smart energy systems, various digital tools for waste reduction, and tools aimed at monitoring environmental compliance.

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[49] Mark, K. (2022). Digitalization of Smart Port. Available: https://doi.org/10.2174/9789815050417122010008

[50] Acciaro, M., Renken, K., El Khadiri, N. (2020). Technological Change and Logistics Development in European Ports. In: Carpenter, A., Lozano, R. (eds) *European Port Cities in Transition. Strategies for Sustainability*. Springer, Cham. Available: https://doi.org/10.1007/978-3-030-36464-9_5

[51] Agatić, A. and Kolanović, I. (2020). Improving the seaport service quality by implementing digital technologies. *Pomorstvo*, 34 (1), 93-101. https://doi.org/10.31217/p.34.1.11

[52] Pruyn, E., Hassel, E. (2022). Editorial: Frontiers in Maritime Transport Chains: Digital and Organizational Innovations in Maritime Transport and Port Operations. *Frontiers in future transportation*, 3 doi: 10.3389/ffutr.2022.869530

[53] https://netzero-events.com/port-digitalization-for-efficiency-and-emission-reduction/

In order to track the digitalisation progress, measure the success of digitalisation initiatives, and identify areas for improvement, it is convenient to establish performance metrics through various relevant key performance indicators. Ports should establish clear KPIs and regularly monitor and evaluate their performance and digitalisation progress against defined KPIs.[54]

Cultivating a digital culture among port employees[55] is a step which may not be so visible or directly obvious, but it is very important for the maximisation of the effectiveness of digital transformation in ports. For these purposes, ports should invest in training and awareness programmes, and even incentives to promote digital transformation amongst employees, assisting them to embrace digital tools and technologies. Optimal process of fostering digital culture could include a culture of collaboration and continuous learning so as to drive successful digital transformation.

Since digitalisation is a process that requires time, inland ports need to implement systems for continuous monitoring and feedback collection, especially due to the reason that the circumstances surrounding ports can change over time, and the digitalisation process itself can be very dynamic, particularly due to the changing needs of the stakeholders. Timely identification of potential issues through monitoring, as well as information gathered through feedback, can prevent unwanted outcomes and implementation problems, while at the same time maintaining high levels of service for the stakeholders and customers alike.

Last, but not least, innovation fostering is another critical component for optimised digitalisation processes in inland ports. In this regard, ports should create such conditions that encourage creativity, experimentation, collaboration, investment in research and development, and forward thinking, in order to match the pace of development of digital tools. This can be done in two ways: with internal resources and with external resources. In case of engaging internal resources, ports can provide opportunities for own staff to propose and test new ideas, technologies, and approaches for addressing challenges and improving port operational practices. In addition, ports have the option of establishing own innovation departments in a myriad of different forms, which proved to be a very effective strategy to capitalise on innovations in digital technologies. Such departments can be responsible for identification of emerging technologies and trends and evaluating innovation opportunities. Moreover, those departments can participate in development projects, pilot projects, proof-of-concepts to test new ideas and solutions, etc. Finally, the innovation department can collaborate with external partners, be they stakeholders, research organisations or private undertakings, with the aim of accelerating innovation initiatives and developments. When external resources are concerned, ports can establish collaboration with IT development companies, research institutions and universities, or they can support spin-off companies. Partnerships with IT development companies can be useful for the customisation and integration of different digital technologies, or tailor-made IoT solutions to meet the specific needs and requirements of ports. Collaboration with research institutions and universities can provide access to the latest advancements in digital technologies and innovation, as well as funding opportunities and grants for innovation projects. Finally, inland ports can opt to support spin-off companies from research organisations or universities that are doing businesses related to innovative technologies development, or that are developing innovative solutions relevant to port operations and port digitalisation. Ports can provide them access to port facilities, infrastructure, and practical expertise and in that way, ports can contribute to incubation and acceleration of growth of such startups, harvesting the benefits from being at the forefront of innovation.

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[54] Paulauskas V., Filina-Dawidowicz L., Paulauskas D. (2021). Ports Digitalization Level Evaluation. *Sensors*, 21(18):6134. Available: https://doi.org/10.3390/s21186134

[55] Almeida, F. (2023). Challenges in the Digital Transformation of Ports. *Businesses*, 3, 548-568. Available: https://10.3390/businesses3040034

4 Interoperability of existing systems

4.1 Definitions, challenges and basic aspects of interoperability

4.1.1 Definitions of interoperability

The concept of interoperability is defined in the ISO/ISO/IEC 2382 Information Technology Vocabulary as the “capability to communicate, execute programs, or transfer data among various functional units in a manner that requires the user to have little or no knowledge of the unique characteristics of those units”.[56]

B2MoS project describes the interoperability as “the ability of independent or heterogeneous systems or organisations to work together in an efficient way and to exchange information using defined standards”.[57]

Interoperability can also be defined as defined as “the ability of two systems to understand each other and to use functionality of one another”.[58] More precisely, interoperability is the exchange of information in an effective, meaningful, and useful manner between different types of information systems, computers, networks, and information and communication technologies (ICTs).[59]

In modern information systems, exchange of data and information is performed automatically, meaning that such systems require little or no direct human intervention.[60] When automatic information exchange takes place between interoperable digital systems, it directly impacts the overall quality of communication between involved stakeholders, as the exchange of information takes place in real time and in maximum quality.

4.1.2 Challenges of interoperability

In a nutshell, interoperability is about the ability of different digital tools and systems to work together seamlessly. This ability of digital tools is a critical challenge in the context of inland port digitalisation. Apart from this, there is a number of other important challenges that need to be taken into account when dealing with the interoperability within and between:

- Single port systems,
- EU inland port systems,
- EU inland ports and connecting EU seaports, and
- Inland ports and stakeholders’ systems

Most typical challenges are discussed in continuation:

Diversity of digital tools already in use: depending on the scope and size of inland ports, as well as on their traffic flows, they can deploy various digital tools, such as PCS, TOS, warehouse management systems, etc. In many cases, these tools are developed by different vendors, leading

[56] https://www.iso.org/obp/ui/#iso:std:iso-iec:2382:-1:ed-3:v1:en

[57] B2MoS (2014). Seaports - River ports systems interoperability, Activity 1 Report. Available: https://www.portialtotirreno.it/wp-content/uploads/2018/03/B2MOS-1.5-ERiverSeaPorts_FinalVersion.pdf

[58] Chen, D., Doumeingts, G., Vernadat, F. (2008). Architectures for enterprise integration and interoperability: Past, present and future, *Computers in Industry*, 59(7), 647-659, Available: https://doi.org/10.1016/j.compind.2007.12.016

[59] Panetto, H. (2007). Towards a classification framework for interoperability of enterprise applications. *International Journal of Computer Integrated Manufacturing*, *20*(8), 727–740. Available: https://doi.org/10.1080/09511920600996419

[60] Görmer-Redding, J. (2018). *Autonomous vehicle groups in urban traffic*. Cuvillier Verlag.

to a high diversity of existing digital tools, which can cause challenges when interoperability is required between these tools. Additionally, focusing on only one developer for digital tools can trigger a so-called vendor lock-in effect for ports, meaning that for every new digital solution ports would have to turn to a single developer/manufacturer, thus reducing their bargaining position and increasing dependency on a single manufacturer, which rarely produces positive outcome.

Similar situation can occur with the so-called legacy systems. These systems are simply the digital tools that port may have deployed for years. Sometimes these systems can become outdated and may not be compatible with more modern digital tools. This, in turn, can represent a challenge for achieving interoperability between various digital tools.

When different systems are incompatible between each other, this can lead to the creation of data silos, preventing data to be exchanged or shared with other tools. This is directly negatively influencing the timely data-driven decision making.

The lack of standards or agreements of which standards to apply for data formats, protocols and interfaces in the port industry is another challenge for interoperability. Different manufacturers may use proprietary formats which are not always easily understood by other tools.

Setting up of different digital systems into an interoperable ecosystem can sometimes result in very complex and costly integration. This happens more frequently in larger ports having multiple terminal operators and other involved stakeholders.

Exchange and share of information within and between different digital systems may pose a risk to data security and privacy. To ensure that confidential and sensitive information is protected when it traffics between systems can be a significant challenge.

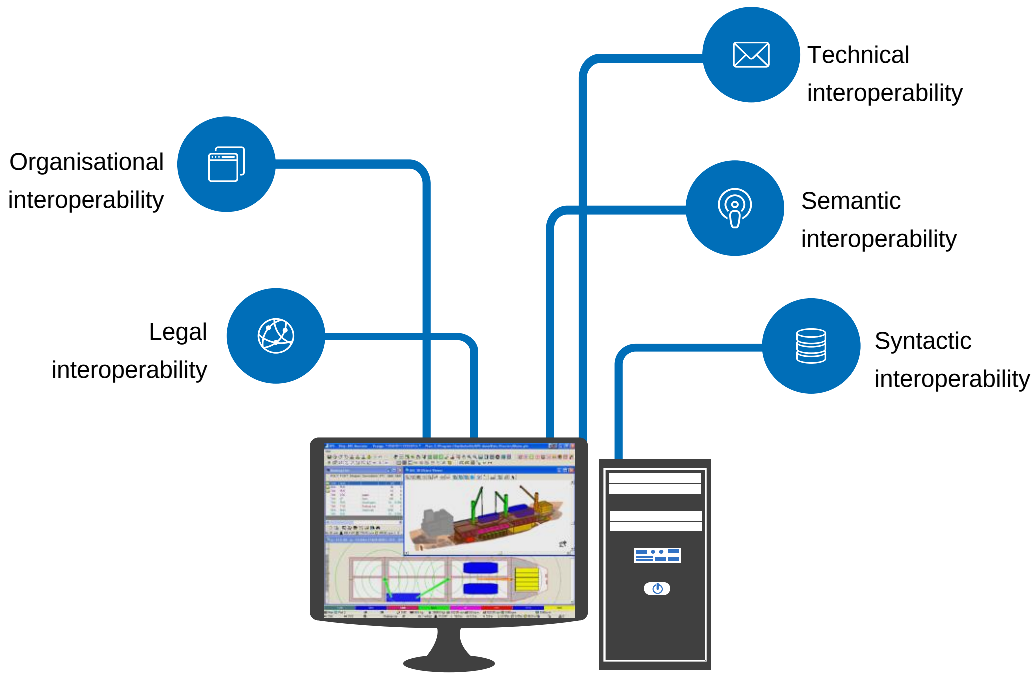
Efficient and effective operations in ports require the exchange of information in real-time communication, especially when automated equipment is involved in operational (cargo handling) processes. Real-time communication between interoperable digital system is another demanding technical challenge.

Last, but not least, since ports are complex systems involving numerous stakeholders (authorities, operators, shipping companies, rail companies, trucking companies, logistics providers, etc.), hence stakeholders collaboration is essential to successful establishing of interoperability between all involved and/or interested parties. Such collaboration can pose an organisational challenge that need to be addressed seriously, as the challenge grows together with the number of stakeholders whose systems need to be integrated into an interoperable “mega-system”.

4.1.3 Basic aspects (or layers) of interoperability

Without entering too deep into technical details, digital tools (systems, software, and platforms) typically have five basic aspects (layers) of interoperability, as demonstrated in the below figure:

Figure 4-1: Basic layers of interoperability



Source: Consortium

Technical interoperability represents the ability of different IT systems, devices, and software to communicate between each other, exchange data, and use the information that they exchange.[61] This layer ensures that different hardware and software components are connected both physically and logically, and that they can accurately transfer data. For example, the technical interoperability layer encompasses the use of standardised communication protocols (e.g., HTTP, TCP/IP) and data formats (e.g., XML, JSON) for data exchange between port systems.

Semantic interoperability, in a nutshell, is the ability of the tools to ensure that the precise meaning of exchanged information is properly understood by any other application or system, including those that were not designed to work together with other systems.[62] It is very important as it enables different systems to interpret and use data consistently and accurately. Semantic interoperability uses standardised data models, taxonomies, an ontologies, to ensure that terms like, “cargo type”, “berth”, or “vessel name” have the same meaning across all systems involved.

Syntactic interoperability is the ability of different digital systems to exchange data using a common format and structure.[63] It ensures that the very structure of data, as well as encoding formats are consistent, so that data can be read and processed correctly by different systems in the port, or by systems involved in the entire supply chain. More simply, this ensures that the systems can read and interpret the data correctly. Syntactic interoperability is achieved through the use of standardised data formats such as CSV, XML, or JSON for structuring data exchanged between, for example, a Terminal Operating System (TOS) and a Port Community System (PCS).

Organisational interoperability focuses on the alignment and integration of business processes, objectives and workflows across different port organisations and their stakeholders, such as

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[61] https://joinup.ec.europa.eu/collection/nifo-national-interoperability-framework-observatory/glossary/term/technical-interoperability

[62] Palojoki S., Lehtonen L., Vuokko R. (2024). Semantic Interoperability of Electronic Health Records: Systematic Review of Alternative Approaches for Enhancing Patient Information Availability. *JMIR Medical Informatics,* Vol.12, Available: doi:10.2196/53535

[63] Hosseini, M., Dixon, B. (2016). Syntactic Interoperability and the Role of Standards, in: Dixon B.E. (Ed.) *Health Information Exchange*, pp.123-136, Academic Press. Available: https://doi.org/10.1016/B978-0-12-803135-3.00008-6.

terminal operators, shipping companies, customs authorities, and logistics providers, to support effective collaboration and the exchange of data. Fundamental elements of organisational interoperability encompass standardised workflows, agreed-upon policies on data governance, and synchronised operational practices. With the purpose of ensuring that all involved stakeholders work together efficiently and consistently. For example, a PCS might coordinate the activities of these stakeholders by implementing shared protocols and communication standards, thus facilitating harmonised port operations.

Legal interoperability represents the ability of involved digital tools to exchange information in strict compliance with relevant legal and regulatory requirements. This layer ensures that the communication and data sharing between different digital tools and systems respects the laws, regulations, and polices related to the protection of privacy and integrity of data. It is very important to ensure that the data exchange between port systems complies with, for example, the General Data Protection Regulation (GDPR)[64] in Europe, Personal Information Protection Law (PIPL)[65] in China, or California Consumer Privacy Act (CCPA)[66] in California.

All these layers together enable digital systems and organisations using those digital systems to work together effectively. This, in turn, contributes to the increase efficiency of port operations.

4.2 Strategic and operational levels of interoperability

In order to achieve seamless interoperability of various digital tools applied along the supply chain, interoperability between digital tools should be considered at two different levels, strategic and operational. The reason for this approach lays in different but complementary roles that each level has in ensuring smooth integration and normal functioning of involved digital tools.

Clear understanding of the distinction between these two levels is essential. First of all, the strategic level includes setting the direction and formulating a vision of the port digitalisation processes, while the operational level deals more with practical implementation of interoperability solutions and other technical aspects of interoperability. These two levels are interconnected and complementary to each other since the strategic decisions set the scene for operational implementation.
When interoperability is achieved at both of these levels, this enables ports to benefit fully from the digitalisation, as well as to create efficient and collaborative networks with their stakeholders. This requires careful planning, timely investments into the appropriate technologies, and full dedication to achieving strong collaborative commitments from all relevant stakeholders.

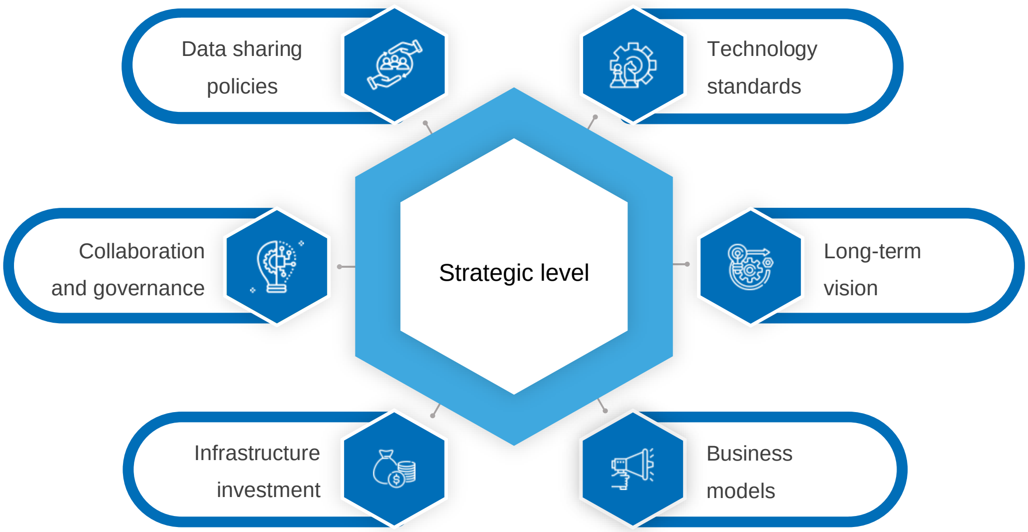
4.2.1 Strategic level

Strategic level in interoperability planning is of crucial importance since it sets the scene for the different stakeholders (within a single port or beyond its boundaries) to work together efficiently and on the long run. At this level, it is necessary to plan the processes which will have the ultimate goal to align different and sometimes conflicting objectives, standards and investment priorities, for the common benefit of smoother collaboration and coordination of activities towards long-term interoperability. In this way, ports and their stakeholders can achieve higher digital efficiency, reduce their operational costs, as well as improve the competitiveness of the entire supply chain. Such proactive planning can help anticipate future developments in digital tools and integrate them easily into the existing systems of ports and their stakeholders.

[64] https://gdpr-info.eu
[65] https://personalinformationprotectionlaw.com
[66] https://oag.ca.gov/privacy/ccpa

Elements of the strategic level of interoperability and shown in the following figure and discussed in continuation.

Figure 4-2: Strategic level in interoperability considerations



Source: Consortium

At the strategic level, determination of technology and data standards needs to be done so as to ensure that different digital systems, within the same port or with external stakeholders, can communicate effectively. This process can encompass the selection of common data standards or Application Programming Interfaces (APIs).

At this level, any planning of interoperability must address the long-term vision and objectives of the wider port community, including all relevant or involved internal and external stakeholders. It needs to include high-level planning and decision-making relevant to digitalisation and necessary levels of data sharing.

Another step in strategic planning of interoperability of inland ports' digital tools includes the development of business models with the goal of encouraging relevant stakeholders to invest in compatible and interoperable digital tools and other solutions that can help in achieving the interoperability. This is very important in case where interoperability goals each beyond the port areas, that is, when they include external stakeholders, such as rail companies, trucking companies, or logistics providers. Such models can include, for example, partnerships between ports and, for example, logistic companies and technology providers, where a shared digital platform is developed.

The next step focuses on the decision-making related to infrastructure investments, such as Port Community Systems or various off-the-shelf or tailor-made middleware solutions that can facilitate the exchange of information and data between different digital tools and stakeholders.

Achieving interoperability on the strategic level also includes the collaboration and creation of governance structures or agreements that determine how various governance entities and business entities, such as port authorities, terminal operators, shipping lines, work together in terms of contributions to the common technologies and tools, duties and responsibilities.

Finally, policies and frameworks related to data sharing, data ownership, access rights and security protocols need to be developed. As increased interoperability leads to improved data sharing strategic decision on what type of data will be shared and with whom need to be made. These decisions are typically part of the data sharing policies.

4.2.2 Operational level

At the operational level, the crosshair is set on the practical integration of digital tools and systems which are used in every day port operations. This level deals with technical aspects that are important to ensure that the involved digital tools can communicate timely and effectively.

Elements of the operational level of interoperability and demonstrated in the following figure and discussed in continuation.

Figure 4-3: Operational level in interoperability considerations

Source: Consortium

The first element of the operational level of interoperability is a system integration. It is of utmost importance in achieving the concrete interoperability so that various digital tools used by different stakeholders can "understand" each other and work together seamlessly.

Ways of data exchange are also defined at the operational level. This includes the frequency of data updates, data formats and communication protocols. Once these aspects are defined, digital systems become enabled to communicate seamlessly and without errors. In this way, real-time collaboration, improved data-driven decision-making, and optimised operations in port and related logistics domains become feasible.

Operational level of interoperability considerations also includes implementing middleware solutions or APIs that act as intermediary software or tools between different digital tools, such as TOS and rail traffic management tool or truck booking platforms. These solutions enable different systems to exchange data without the need for full integration of such systems.

Real-time connectivity is another aspect operational interoperability, where real-time exchange of data needs to be ensured. For example, when a barge operator updates the foreseen or estimated time of arrival (ETA) to a port, this information needs to be immediately accessible to the terminals TOS.

Standardised protocols encompass the use of standardised communication protocols and formats such as EDI, XML or web-based services such as REST or SOAP. SOAP and REST are two different approaches to API design. The SOAP approach is highly structured and uses XML data format, while REST is more flexible and allows applications to exchange data in multiple formats.

User training involves the education of port personnel and external stakeholders to effectively use interoperable digital tools.

4.3 Strategies for interoperability improvements

Digital interoperability of inland ports narrows down to the ability to achieve quick, seamless, secure, and reliable data and information exchange between companies[67] included in the port operations or in the wider supply chain. Inland ports can opt between many strategies that have the ultimate goal to achieve such interoperability, which, in the end, can benefit not only ports but all stakeholders and even final users. These strategies involve technical and organisational measures. Below table contains the most typical (but non exhaustive) interoperability improvement strategies, of both technical and organisational types.

Table 4-1: Strategies for interoperability improvements

Strategies	Short description
Common data standards	Common data standards and formats have to be established so that all systems need to comply with, for the purposes of simplified and smooth data sharing and integration.
Middleware solutions	Middleware platforms and software act as intermediaries between different incompatible systems, translating data and requests between them. These solutions can help with the routing and synchronisation of data, as well as with data transformation.
Application Programming Interfaces (APIs)	Application of APIs allow different systems to communicate with each other. APIs define the methods and data formats necessary for interactions, making the integration of systems much easier.
Data integration platforms	Ports can invest in data integration platforms or tools in order to facilitate the data flow between different systems. These platforms can work with various data sources and formats, enabling easier data mapping and transformation.
Master Data Management (MDM)	MDM solutions can be applied in order to create a singular and consistent source of the so called “data truth”. This procedures ensures that the data is accurate and synchronised across different systems, which contributes to the reduction of inconsistencies and errors.
Scalable architecture	When designing their digitalisation processes, ports should always have scalability in mind. This will allow the “growth” of digital tools along with the increase in port operations. Scalable architecture can handle the increased load without compromising its ability to integrate and operate with other systems effectively.
Cloud-based solutions	Ports can also opt for adopting cloud-based solutions as they are typically designed with interoperability as one of its important features. Cloud-based tools can provide a unified environment for multiple applications and data sources. Some of PCS are cloud-based.

[67] Pan, S., Trentesaux, D., McFarlane, D., Montreuil, B., Ballot, E., Huang, G.Q., (2021). Digital interoperability in logistics and supply chain management: state-of-the-art and research avenues towards Physical Internet. Computers in Industry 128, 103435. Available: https://doi.org/10.1016/j.compind.2021.103435

Strategies	Short description
Third-party integration services	Another option for ports is to use the third-party integration services, with prior evaluation of these services for their compatibility with existing tools in the port.
Data governance	Ports should implement robust data governance practices to manage data quality, integrity and security. Such frameworks contribute to the maintenance of the data consistency and reliability in all digital systems involved.
Feedback mechanisms	Port have to gather inputs from various users and stakeholders on their experiences in collaborating with or using of ports' digital tools, in terms of identification of interoperability issues and improvement ideas.
Testing and validation	Before full deployment of any interoperability solutions, port should test and validate those solutions in order to identify and resolve potential issues. This testing is a very convenient way to reduce or prevent the risk of disruptions in port operations.
Monitoring and maintenance	Deployed interoperability solutions need to be monitored and maintained continuously, including regular updates and patches.
Collaboration forums	Ports should be present in different industry collaboration forums and organisation dealing with port technology and digitalisation. Being always on the technological edge can result in improvements in interoperability.

Source: Consortium.

Detailed explanation of each point from the above table is given in the following sections.

4.3.1 Common data standards

Being a fundamental element of achieving interoperability of various digital systems, common data standards provide a common framework for data structure, formats, and semantics. This ensures that different systems and tools can exchange data seamlessly.[68]

First of all, common data standards define the formats in which data should be structured, such as:

- JSON (JavaScript Object Notation): A lightweight, human-readable format widely used for data interchange. Its simplicity and compatibility make it a popular choice for APIs and web services, or
- XML (Extensible Markup Language): A versatile markup language that structures data hierarchically. XML has been foundational for data exchange in various domains.

These standards enable consistent understanding and interpretation of data by different systems.

In addition, data models, which are often included in the data standards, are designed to describe the structure and relationships between data elements. Moreover, standards can include the specification of communication protocols for data exchange, such as HyperText Transfer Protocol (HTTP), REpresentational State Transfer (REST), or Message Queuing Telemetry Transport (MQTT).[69] Common data standards are also important for APIs which define the methods and so-called endpoint through which different system can interact. Standards applied in API design ensure that APIs are user-friendly, consistent, and properly documented.

Another important role of data standards is the semantic interoperability, which ensures that data shared between different digital systems has a unique and common understanding of its meaning.

[68] https://fastercapital.com/topics/the-role-of-standards-and-interoperability-in-facilitating-seamless-data-transfer.html/1
[69] https://www.emqx.com/en/blog/the-easiest-guide-to-getting-started-with-mqtt

Here, standardisation is required for taxonomies, ontologies, and controlled vocabularies to clarify the data interpretation.[70]

Implementation of common data standards ensures that data collected, generated, or processed by one digital tool in a port can be understood and used by another port digital tool or by digital tools of involved stakeholders.

4.3.2 Middleware solutions

Middleware solutions have a crucial importance in interoperability of port digital tools, both internally and externally. Middleware is essentially a software that serves as an intermediary between two or more incompatible digital tools (software, applications, platforms, etc.) enabling their communication, exchange of data and integration. Middleware solutions translate data from one format to another, for example, from HTTP to MQTT, acting as an interpreter for two or more digital tools that use different data formats, that is, for digital tools that do not “speak the same language”. This can be very important when new digital tools are introduced in a port that already has legacy systems.

Additionally, middleware can act as “message broker”, meaning that it can perform asynchronous communication between digital tools. In a nutshell, these intermediary tools can store and forward messages when both the sender and receiver are available, which very important for real-time data sharing.

Middleware can also perform the data transformation, apart from just data translation. Data transformation includes the restructuring and reformatting of data from one system according to the requirements of the destination systems. This is usually called the extract, transform and load (ETL) data from one digital tool to another.

One of the very useful features of middleware solutions is their ability to serve as security and access control tools. In this way, ports can use middleware to manage access control, authentication and authorisation to specific data or services. They can also include monitoring and analytics capabilities, which allows ports to track the overall system performance, identify bottlenecks and optimisation possibilities within data flows. Middleware solutions are typically designed with scalability in mind, enabling not only regular upgrades but also the handling of increased data flows or integration requests. In inland ports, there is a typical need to integrate diverse systems and tools, including port community systems, terminal operating systems, digital twins, etc. Moreover, middleware solutions are typically adaptable and customisable to specific need of ports, making them a very handy solution for most, if not all, interoperability issues.

An Enterprise Service Bus (ESB) is a software architecture model used for designing and implementing the interaction and communication between different digital tools in a service-oriented architecture (SOA). It acts as a middleware layer that facilitates the integration of various services and applications, enabling them to communicate with each other seamlessly.[71] ESB has a role in message transformation and routing, transforming data formats between different systems, ensuring that data sent by one system can be understood by another. It can route messages based on content or predefined rules, directing data to the appropriate systems. For example, environmental data from sensors can be sent to the environmental monitoring system, while cargo status updates are sent to the PCS. ESB can orchestrate various services and processes through coordination of the interactions between multiple systems. This helps in managing complex

[70] https://internationaldataspaces.org/semantic-interoperability-a-common-language-for-data-sharing/
[71] https://www.ibm.com/topics/esb

workflows, such as coordination of cargo handling between TOS and PCS. ESB supports various communication protocols allowing different systems to communicate with each other even if they use different protocols.

4.3.3 Application programming interfaces

An Application Programming Interface (API) is a set of rules and protocols that defines how two software systems can communicate with each other. APIs have a very important role in achieving interoperability between port digital tools, and between internal port digital tools and tools of different port stakeholders within and outside of ports. These solutions provide standardised methods for communication and interaction between different digital tools, primarily software applications. An API works by allowing a client software system to send requests to a server software system, which then processes the request and returns a response. This enables the client to interact with the server and access its functionality and data in a structured and predictable way.[72] In the context of port systems, APIs serve as the crucial link which allows exchange of data and functionality sharing between, for example, the terminal operating system (TOS) and external systems such as digital tools applied by shipping lines, trucking and rail operators, and logistic providers.[73] This integration is of crucial importance for maintaining communication in real time, for the enhancement of operational efficiency, as well as for facilitation of collaborative workflows along the supply chain. Data that is exchanged is presented in a format that can easily be captured and processed by other involved digital systems.

Typically, APIs ensure that data is structured and exchanged in a consistent manner, since they comply with industry standards and protocols. Due to this reason, typical API make data and functionalities accessible only to authorised users and systems, allowing ports to have full control over access to their digital tools and services. Moreover, APIs are designed in such way to enable easy integration of external services, such as weather forecasting, customs clearance or even predictive maintenance solutions.

Ports may use APIs to connect with Internet of Things (IoT) devices and sensors for real-time monitoring of assets and environmental conditions in the port area.[74] This integration is of high importance for environmental management and safety.

Ports can choose the API type that best suits their requirements and integrate them into their digitalisation architecture. APIs are instrumental in fostering interoperability, allowing ports to operate efficiently, enhance their services, and collaborate effectively with their stakeholders.

4.3.4 Data integration platforms

Data integration platforms are another convenient strategy to deal with interoperability issues in ports as they collect and aggregate data from various sources within the port domain, including data from TOS, cargo tracking systems, RIS, AIS, environmental sensors, and other data sources. Once collected, data is transformed into a standardised format or structure, which ensures that data is consistent and compatible with all involved digital systems. For example, data from legacy systems in ports can be transformed into a format which newer applications can understand and process. Moreover, data integration platforms can enable the real-time flow of information, which, in

[72] https://sinay.ai/en/how-does-an-api-work-and-how-it-can-help-ports/
[73] https://contpark.com/api-integration-for-container-terminal-systems/
[74] Giménez, P., & Llop, M. (2020). Interoperability of IoT platforms in the port sector. *Proceedings of the Transport Research Arena (TRA 2020)*, Helsinki, Finland, 27–30 April 2020. Available: https://www.researchgate.net/publication/339883632_Interoperability_of_IoT_platforms_in_the_port_sector

turn, enables ports to make data-driven decisions in short time. This is important in the processes of vessel scheduling, security monitoring and environmental data analysis.

Scalability is another important feature of the most data integration platforms, as they are typically designed to scale with the growing data demands of the port, and in parallel with the increase in port operations. Since many ports are using various cloud-based solutions, data integrating platforms can easily integrate cloud services with on-site digital tools, which can allow ports to benefit from cloud technology while maintaining compatibility with existing digital infrastructure. In addition, data integration platforms can perform data quality assurance measures such as data cleansing, filtering, validation, and detection of errors.

As other technologies, data integration platforms can integrate IoT data into their interface. For example, they can present data collected by IoT-based environmental sensors strategically placed throughout the port.

Last but not least, data integration platforms enable collaboration between various stakeholders in the port community, such as various authorities, trucking companies, rail operators, shipping lines, etc.

One example of application of data integration platforms as an interoperability solution is the case of North Sea Port[75]. North Sea Port has adopted an iPaaS (integration platform as a service) platform to link on-board devices to its port management system to get barge data that can optimise port operations and eliminate paperwork for boat captains.[76] Ships and barges use AIS (Automatic Identification System) systems, which include VHF transceivers and other transponders complemented by GPS technology to transmit information about position, course and speed. Developer of the data integration platform developed a mobile app for barge skippers that allows them to add data to the basic AIS information, including the cargo they are carrying, what they will be unloading at which dock, and how long they will be staying at a particular port.

The barge information is transmitted to a cloud-based data integration portal designed to connect cloud and on-premises applications and data. Data from the portal is, in turn, passed on to the port’s in-house port management system where it is used for further planning of port operations.

4.3.5 Master data management

Master data management (MDM) has a specific role in achieving interoperability between different digital systems applied in ports. MDM is a conglomeration of processes, governance, policies, and tools that are aimed at consistent management and maintenance of an organisation’s critical data, ensuring its accuracy, reliability, and accessibility throughout various digital systems.[77]

MDM creates a unique set of data definitions, taxonomies, and ontologies that all involved digital systems in a port must comply with. It also enforces data quality standards and governance policies aimed at ensuring the integrity and reliability of data.[78]

In the context of ports, it needs to be emphasised that each of the multiple digital systems that may exist in a port handle data in their own way. MDM harmonises all this data from various systems/sources into a unique and standardised formats, which allows different digital tools to

[75] https://en.northseaport.com
[76] https://www.cio.com/article/193166/north-sea-ports-ipaas-iot-system-integration-streamlines-operations.html
[77] https://www.sap.com/products/technology-platform/master-data-governance/what-is-mdm.html
[78] https://consultport.com/for-companies/a-guide-to-master-data-management-with-medtech-case-study/

understand and use the data seamlessly. For example, data coming from cargo management, terminal operations, logistics or environmental monitoring systems all need to be aligned so that they could be used by different digital systems. In addition, MDM facilitates data sharing among various systems and platforms within the port domain. This is done through the creation of a centralised repository where master data such as information on ships, cargo, customers, trucking companies, rail operators, etc. is stored. This ensures that all systems within the port ecosystem access the same accurate and up-to-date information, reducing inconsistencies and errors. Ports have reference data, such as vessel names, location codes, cargo types, and more. MDM manages this reference data centrally, ensuring that all systems use the same reference data, thereby reducing errors and inconsistencies.

One of the important features of MDM is the ability to create master data records. These records represent single-source versions of data entities such as cargo owners, cargoes, terminals, vessels, locations, etc. MDM are designed in such way to maintain a history of data changes, allowing ports to track data revisions and updates along the time line. Since ports often have multiple locations and stakeholders, MDM ensures that data are synchronised among these distributed entities, thus maintaining a single version of the data truth throughout the port domain. Finally, MDM solutions are designed to scale up with the growth of the port and its need for data.

4.3.6 Scalable architecture

Scalable architecture is one of the critical components in the quest for achieving continuous interoperability between digital tools applied in port realm. It provides a basis that allows ports to expand and adapt their digital infrastructure in such way to accommodate new digital tools and technologies, while at the same time maintaining seamless and efficient data flows. This flexibility also ensures that interoperability is not jeopardised as the port environment evolves.

4.3.7 Cloud-based solutions

Cloud-based solutions are designed with interoperability as one of the priority requirements. These solutions provide the infrastructure and services that are needed to allow the effective exchange of data and functionalities among different digital systems deployed by various port stakeholders or participants in the supply chain.

Cloud-based solutions have a centralised repository where relevant data from different digital systems can be stored, managed, and accessed. Such centralised approach greatly simplifies data sharing and access, allowing all relevant stakeholders to easily retrieve data. Data is stored in a standardised and accessible format, thus maintaining interoperability between different systems that feed the repositories or that retrieve data from them. One of the very handy features of cloud-based systems is the ability to make real-time data sharing possible, which is very important in dynamic environments such as ports and terminals.

Cloud-based platforms are inherently scalable, allowing ports to adjust their digital infrastructure according to the needs. Cloud-based platforms can accommodate virtually all types of changes in digital systems, whether there are completely new systems introduced or the existing ones are updated. They typically come with integration services possibilities, including API, so that they can facilitate communication and interaction between different digital tools and systems of involved stakeholders. The integration of, for example, ports and customs information systems in a cloud environment represents a significant step forward in optimising global trade operations. This decision is based on several factors, such as trade volume, IT budget, data sovereignty and growth aspirations in the medium to long term. Ultimately, whether anchored to traditional on-premises systems or moving onto the cloud, the chosen path should align with the organisational strategy to ensure that ports and Customs operations remain efficient, secure, and poised for the future of global trade.[79]

In addition, cloud-based platforms frequently offer collaboration features, such as shared workspace and communication tools. This directly promotes collaboration of different port stakeholders, on both business and government side. In many cases, cloud-based platforms can be accessed from various devices and platforms, such as computers, tablets, or mobile phones, allowing both office and field-like users to access them.

In terms of security, cloud-based solutions deploy robust security measures and compliance standards such as data encryption, access control and authentication protocols. From the cost-efficiency point of view, cloud-based solutions are in better position then traditional on-premises systems as ports can avoid significant upfront hardware and software investments. Cloud providers frequently implement disaster recover and redundancy measures to provide the continuity of services in case of crashed or any other unexpected events. This is very important from the point of view of reliability and the overall availability of port digital systems as it minimises downtimes and data losses.

4.3.8 Third-party integration services

Third-party integration services are important for achieving interoperability among various digital systems of ports and their stakeholders by connecting them into a unified digital ecosystem with all accompanying data and functionalities.

Similar to cloud-based services or middleware solutions, the third-party integration services enable various digital tools to be connected and work in harmony with each other, such as TOS, warehouse management systems, customs systems, or gate operating systems. This integration ensures that the data flow is streamlined in terms of collection, processing, and distribution, thus avoiding data silos and redundancy. Data is share among stakeholders in real-time, thus improving the data-driven decision-making processes. For example, integrating the vessel management system with the TOS can streamline the loading and unloading process, thus reducing idle times, and improving turnaround times.

Integration services bridge the gap between different stakeholders and their digital tools, ensuring cross-platform communication and synchronised operations throughout the entire supply chain. This can also offer better experience to port users such as shipping lines, cargo owners, logistic providers, etc. These integration services typically include data standardisation and transformation capabilities, which ensure that data can be shared and interpreted uniformly across different systems. This is very important from the point of view of the minimisation of errors and maximisation of data accuracy.

4.3.9 Data governance practices

Data governance practices encompass processes and activities such as data quality assurance, data security and compliance, data standardisation, data ownership and stewardship, data life cycle management, data interoperability standards, etc.

These practices set standards and processes for data quality. Since ports deal with huge amount od data from different sources (TOS, gate operating systems, RFID tags, load sensors on cranes

[79] https://mag.wcoomd.org/magazine/wco-news-102-issue-3-2023/ports-customs-information-systems-cloud-environment/

and quays, environmental sensors, etc.), their quality in terms of accuracy, consistency and completeness is of crucial importance for reliable interoperability. Moreover, data governance frameworks provide the structure for data protection, access control and compliance monitoring which is also important because ports must comply with various data security regulations, especially when they deal with sensitive cargo and personal information. In addition, data governance defines data ownership and stewardship roles.

Data governance practices also include the definitions of data standards and formats in order to enable easier share and understanding of data between different users and their systems. These practices can also include the definition of interoperability standards, in terms of guidelines on how different digital systems should exchange data.

Data access, control and lifecycle management are also important features of data governance practices as they encompass access control policies and the definition of the ways of data management through the entire lifecycle of data. The latter includes data retention policies and archiving procedures.

Other elements of data governance practices include, but are not limited to, metadata management (data about data), data catalogues and inventories, data auditing and monitoring, data privacy, conflict resolution, etc.

Implementation of robust data governance practices allows ports to build healthy foundation for posterior deployment of interoperability solutions since the data is exchanged seamlessly, accurately, securely and on compliance with regulation. This has a direct and positive influence on the efficiency of port operations.

4.3.10 Feedback loops

Feedback loops refer to the constant or frequent communication with stakeholders about their satisfaction and experience with interoperability solutions deployed by ports. Such communication enables ports to easily identify issues, optimisation potentials and alignment of deployed technology solutions.

Apart from potential issues and optimisation potentials, feedback mechanisms provide direct and thorough understanding of the needs and preferences of users and stakeholders, which, in turn, is essential for the design of user-friendly digital tools. User-centred designed is usually linked with higher adoption rates and improved interoperability. Port authorities can have specific objectives, such as improvement of environmental performance of port activities or increase of operational efficiencies, so user and stakeholder feedback can give insights into whether digital tools are effectively contributing to these goals, or some adjustments are needed.

In addition, feedback mechanisms are very useful in identification of potential risks. For example, users may report security concerns or vulnerabilities and ports can take timely and appropriate actions to mitigate these risks, this preventing potential threats to interoperability or data integrity.

Finally, feedback guides the evolution of digital tools to remain relevant in view of the highly dynamic environment in ports and ever-changing requirements from the port stakeholders in view of the operations and data requirements.

4.3.11 Testing and validation of interoperability solutions

Testing and validation of interoperability solutions is yet another convenient strategy to maintain good levels of interoperability in the port environments or throughout the supply chain. This is necessary to ensure that various port digital tools and systems work seamlessly and maintain the required levels of efficiency, data accuracy and operational performances, prior to their full deployment.

First of all, testing and validation are a very important mechanism for quality assurance. These procedures can identify issues and discrepancies from the design or order specifications, be they in the domain of data exchange, communication, or overall performance. Moreover, testing demonstrates that interoperability solutions can (or cannot) maintain data integrity during data transfers between different systems, preventing the corruption or loss of data. Only rigorous testing in the real world of ports can ensure that the systems operate reliably and as required.

Testing can also reveal any errors or inconsistencies in data exchange and/or how different data interact between each other, or if the interoperability solutions can be scaled in parallel with the growth of operations level or requirements for data from port users.

Another important issue that should be tested before full deployment of chosen or considered interoperability solutions are the testing of security, where potential vulnerabilities or breaches can be identified. Controlled testing environment provides ideal conditions to test and validate the risk mitigation measures for known or foreseeable risks, and also to identify new risks that were not easily identifiable during specification or design phases of interoperability solutions. This is especially important when testing interoperability solutions with external partners and when ports work with third-party service providers, as it helps verify that third-party integrations are aligned with port needs.

A few more aspects of interoperability solutions are tested during the testing and validation phase: consistency, operational resilience, and downtime reduction. In view of the consistency, interoperability solutions should be tested that data sent from one system to another is consistent and maintains its meaning. Since ports need to function under adverse technical, operational, and even meteorological conditions, the resilience of interoperability solutions needs to be tested, as it ensures that port operations can continue even under challenging conditions. Finally, thorough testing of interoperability solutions reduces the probability of systems failures or unexpected downtimes during real-world operations, which is especially important for ports where every minute of downtime can be very costly.

4.3.12 Monitoring and maintenance

Similar to testing and validation prior to the full deployment of a chosen interoperability solution, monitoring is performed after full commissioning of the chosen interoperability solution. This goes hand-in-hand with maintenance activities.

Continuous monitoring of the performance of interoperability solutions allows ports to track, inter alia, response times, data throughput and resource utilisation. Monitoring also allows ports to detect issues, errors, or deviations from designed or expected performance in real-time. In addition, monitoring can identify unusual activities or security breaches, which is essential for protecting sensitive data and ensuring the overall integrity of digital systems. Monitoring of data exchange between systems can ensure data accuracy and consistency.

Monitoring provides ports necessary inputs for resource optimisation, capacity planning (in terms of digital tools and interoperability solutions) and mitigation of risks related to system interactions and interoperability. For ports working with service providers, monitoring contributes to the efforts that service level agreements are respected according to the contract. It provides data to validate whether contracted services are delivered as agreed.

Finally, regular maintenance practices based on monitoring data have a very important role in preventing unexpected system failures. Activities included in maintenance cover, among others, software updates, hardware inspections, patch installations, etc.

4.3.13 Collaboration forums

Collaboration forums can take various forms, such as industry associations, organisations, working groups and similar forms. These forums typically bring diverse stakeholders from the port and shipping industry, as well as software and technology providers, developers, and vendors. Collaboration forums have the prime purpose of sharing of knowledge, best practices, experiences, and discussions on common challenges.

Typical benefits of such forums include the definitions of industry standards and guidelines for interoperability, problem solving and networking.

Some of the examples of collaboration forums in the port industry, related to the port digitalisation topics, including interoperability are the following:

- International Port Community Systems Association (IPCSA). IPCSA is a specific example of a collaboration forum which focuses on development and introduction of port community systems (PCS) in ports. It gathers PCS operators, stakeholders and experts with the purpose of developing standards and sharing best practices for PCS interoperability.
- Digital Container Shipping Association (DCSA). DCSA is an industry forum having the standardisation of the use of digital technologies in container shipping as one of its major goals. Specifically, in terms of interoperability, DCSA has the following objective:
  - *DCSA envisions a fully interoperable global trade ecosystem in which all stakeholders have on-demand access to accurate, timely digital shipping data and documentation that flow seamlessly across the end-to-end container journey. By aligning shipping data, processes, and technology, DCSA standards create interoperability, which brings increased efficiency to all stakeholders. With DCSA standards in place, stakeholders can seamlessly exchange standardised digital data, enabling the automation of manual and paper-based processes such as cargo tracking, port calls, equipment management and documentation. Widespread adoption of DCSA digital standards will optimise efficiency and lower costs while improving the reliability and sustainability of international trade*.[80]

4.4 Interoperability between different port systems

In this section, the interoperability of digital tools used within four different port systems will be briefly examined, as required by the Terms of Reference for this Study:

- Single port systems.
- EU inland port systems.
- EU inland ports and connecting EU seaports.

[80] https://www.dcsa.org/our-mission/interoperability-efficiency

- Inland ports and stakeholders' systems.

Interoperability between different digital tools within a single port and of digital tools of actors in all four port systems is an important elements of an efficient port ecosystem and port-centred supply chain.

Objectives of such interoperability are listed in continuation:

- Seamless data flow. Port operations involve numerous stakeholders, such as port authorities, terminal operators, barge operators, customs, rail and road companies, logistics providers and similar, all of them relying on specialised digital tools and systems for their own operations. When operations are underway, it is of utmost importance that the data flows seamlessly between all digital tools and systems that are involved in the process. In addition to this, stakeholders need to share critical information between them, such as container tracking, barge location and schedules, cargo details, customs documentation, etc. Any setbacks in the seamless communication between digital tools used by the involved stakeholders leads to deficiencies, delays, and costly errors.
- Efficiency and productivity. Interoperability solutions reduce the need for duplicated data entry. Without such solutions, data entered in one systems would typically have to be re-entered manually in another digital tool, opening space for errors and extra time needed for data re-entering. Moreover, when port digital systems work together with stakeholders' digital systems, work processes become more streamlined. For instance, data needed for the customs can be fed directly from the terminal operating system, thus reducing processing times and avoiding double work.
- Improved visibility and decision-making. Interoperability solutions allow stakeholders to have access to the right data at the right time, which enables better decision-making. This is especially important in busier ports with large saturation of operations, vehicles, vessels, vehicles, and processes fluctuating simultaneously. In case of ports, for example, data obtained from the vessel management digital tools at the right time can help in optimal berth allocation.
- Security and compliance. Any data is at risk when being transferred from one system to another. Interoperable platforms, or interoperability solutions, typically include robust security measures to protect sensitive data from breaches or unauthorised access. Additionally, many stakeholders need to comply with industry regulations and data protection legislation, and for these reasons interoperable solutions need to ensure that data sharing complies with such requirements.
- Cost savings. Maintenance of multiple systems that are not interoperable can frequently be very costly. Integration of digital systems can significantly reduce IT maintenance expenses, as well as licensing costs.
- Scalability. Increase of port operations in terms of volumes, vehicles and vessels usually trigger the introduction of new or upgraded digital tools and systems. Interoperability enables seamless integration of new or upgraded tools into the existing overall system.
- Customer experience. Delivery of services by ports and their stakeholders in an efficient and effective manner frequently depends on the harmonised work of digital tools, making improved customer experience one of the important objectives set upon interoperability solutions in different categories of port systems.
- Competitive advantage. Ports that are quick in adapting to changing market conditions and advancements in port digitalisation through interoperability are likely to gain a competitive edge in the port sector.

Peculiarities of interoperability of each of the four categories of port systems will be examined in continuation.

4.4.1 Interoperability within single port systems

Interoperability within single port systems refers to seamless integration, communication and data exchange between various digital tools applied in a single port. These tools may include, for example:

- Port Community System,
- Terminal Operating System,
- IoT based sensors gathering and transmitting data on crane load, quay load, traffic congestion in ports, crane health and maintenance needs, cargo temperature and volumes, proximity sensors, environmental KPIs, etc.,
- Real-time location systems (RTLS),
- AI based traffic forecasting digital tools,
- Port digital twins,
- Intra-port rail traffic management system,
- Customs digital tools,
- Vehicle booking systems,
- Cargo tracking digital tools,
- and many other digital tools.

Interoperability between these digital tools is needed to facilitate cooperation between various stakeholders, synchronisation, and integration of different digital tools with the overall purpose of efficiency increase and smooth performing of linked operations and data exchange. It is typically achieved through the integration of various digital tools, with the objective of providing seamless data exchange, efficient communication between different tools, as well as coordinated operations. This involves using standardised protocols, common data formats, as well as integration frameworks, which is all needed for the effective interaction of all tools/systems involved.

To achieve interoperability between the involved digital tools, the following minimum components are needed (for example):

- Standardised communication protocols, such as widely accepted HTTP, REST, MQTT, etc., to allow uniform data exchange.
- Common data standards to harmonise data formats and terminologies between involved digital systems.
- Middleware solutions for the facilitation of communication between different systems and for the management of data flows.
- API management for the purposes of communication and seamless data exchange between different systems.
- Master data management (MDM) with the centralised repository of key reference data needed for the consistency between different systems.
- Data governance, including policies for data quality management, security, and compliance.

Based on the above listed digital tools, an interoperable port ecosystem would have the following features:

- Integrated operations would be enabled by, for example, data from IoT sensors, RTLS, and AI-based digital tools, which would feed the PCS and TOS, providing a comprehensive view of port operations in a given moment or period.

- Seamless data sharing of, for example, data on crane loads, traffic congestion, cargo features and position, would be enabled without manual intervention.
- Coordinated actions would be possible as, for example, customs digital tools, vehicle booking systems and cargo tracking applications would coordinate to streamline the process of cargo clearing for export or import.
- Improved decision making would be enabled thanks to the port digital twin which would use data from various digital tools to simulate and optimise port operations, and thus improve the efficiency and resilience of port operations.

Interoperability of digital systems also includes carefully designed architecture. The "architecture" of interoperable digital systems refers to the structured design and framework that defines how different systems, components, and technologies interact and work together to achieve the targeted level of interoperability. Such architecture includes the following:

- Integration layer, usually in the form of a middleware, which facilitates communication between different digital tools and systems.
- API gateway, which manages and secures API traffic between systems.
- Data lake, that is, a centralised data repository, having a role of collecting, processing, and storing data from various sources.
- Service-oriented architecture, which includes the so-called “microservices” which handle specific functions and can be independently developed, implemented, and maintained. These specific functions refer to, for example, cargo tracking microservices, vessel scheduling microservices, traffic management microservices, environmental monitoring microservices, etc. Traffic management services, for example, use IoT sensors and AI-based forecasting tools to monitor and control the flow of trucks, trains, and other vehicles within the port.
- Event-driven architecture, where systems communicate through various types of events related to changes or updates in the state of different components or processes. For example, in vessel arrival/departure events there are three elements: event itself – when a vessel arrives or departs from port, trigger – automatic identification systems (AIS) detect vessel arrival or departure, and action – which updates the scheduling system, triggers cargo loading or unloading, notifies customs and logistic providers, etc.
- Security layer, which takes care of data security, privacy, and compliance with regulations through encryption, authentication, and mechanisms for authorisation.

Can a Port Community System be considered as an interoperability solution?

Port Community Systems (PCS) can be used as a tool for interoperability in ports to a certain level. Although, technically speaking, PCS is not an interoperability tool, it does provide a “bridge” between various digital tools in the port, through its integrative role. The bridging and integrative roles of PCS are facilitated by numerous interoperability solutions, such as standardised communication protocols (like HTTP, REST, or similar) that are embedded in PCS, use of data formats (such as XML, JSON, etc.), or APIs that are developed and managed within PCS[81] having the objective to enable different digital tools to interact effectively, thus ensuring the smooth flow of data between different systems.

Thanks to its own embedded interoperability solutions, PCS can act as a centralised platform where data from different digital tools and systems, systems such as Terminal Operating Systems (TOS), IoT-based sensors, real-time location systems, AI-based traffic forecasting tools, port digital twins, and customs digital tools converge for the benefit of all involved stakeholders. PCS can integrate workflows from different digital systems and automate data exchange between them. For example,

[81] Sahu, S., Saragiotis, P., Olivier, P. (2023). *Port Community Systems: Lessons from Global Experience*, Conference edition, Worl Bank Group and International Association of Ports and Harbors.

some PCS can initiate actions in the TOS on the basis of data received from IoT sensors in the port, or from real-time traffic management tools.[82]

Moreover, most PCS can be easily integrated with digital tools of external stakeholders, such as logistic providers, which can improve and speed up the management of intermodal transport in ports.[83]

Thanks to its embedded interoperability solutions, PCS can also be integrated with, for example:

- IoT based sensors, where the PCS collects data from IoT sensors monitoring, for example, crane load, traffic congestion or environmental conditions. This data can be made accessible, if so agreed, to interested stakeholders – for example to terminal operators, who can use the data for the improvement or adjustment of their operational practices and performance.
- Customs digital tools, to enable the smooth clearance process and exchange of documents, thus speeding up the cargo flows.
- AI-based tools and predictive analytics tools, where PCS can benefit from, for example, prediction of congestion situations, which can be used to optimise the port traffic.
- Real-time location systems, in order to track the movement of cargo and vehicles, providing accurate and real-time information to stakeholders.

It needs to be noted that PCS, acting as a shared platform or a central hub for data exchange between various port stakeholders, actively supports the interoperability of different digital tools within single ports.

One of the crucial integration vectors in ports is that of PCS and TOS integration. TOS manages the day-to-day operations in a port terminal, including the movement of handling equipment, and movement and storage of cargo. TOS tracks container movements, allocate resources and optimise terminal performance. Effective communication between TOS and PCS requires common data standards and protocols, as well as APIs, which ensures that data on container status and locations, as well as vessel schedules, can be accurately shared and synchronised between involved digital systems.

In addition, many PCS are designed to act as Platform as a Service (PaaS), meaning that they do not act only as data exchange hub, but that they also offer certain services, such as, pre-notifying barge visits and containers to terminals and depots. An example of such PCS can be found in the Port of Rotterdam, where their PCS (Portbase[84]) offers such services to barge operators through the so-called Hinterland Container Notification (HCN) Barge, which facilitates advance notification of barge visits and cargo to sea and inland terminals and depots. This service makes it easy to pre-notify the barge visit and all cargo for inland vessels to sea and inland terminals and depots, allowing them to prepare for the visit properly, thus speeding up the turnaround time of a barge in port. It also enables users to receive automatic feedback on the status of their pre-notified containers, allowing for timely adjustments and preventing mistakes. The service can be used via an API system interface or through a web page.

Environmental sensors strategically placed throughout the inland port can be integrated with PCS, with the objective of monitor and manage various environmental conditions, such as air quality, water quality, noise levels, and weather conditions. These sensors collect real-time data on various

[82] Inutsuka, H., Ichimura, K., Sugimura, Y., Yoshie, M., Shinoda, T. (2024). Study on the Relationship between Port Governance and Terminal Operation System for Smart Port: Japan Case. *Logistics*, 8(59). Available: https://doi.org/10.3390/logistics8020059

[83] https://accudire.eu/en/accudire-for-logistics-operators/interoperability-with-ports/

[84] https://www.portbase.com/en/services/hinterland-container-notification-barge/

environmental parameters, including air and water quality, noise levels, and meteorological conditions, whereas PCS aggregates this data, allowing port authorities and other stakeholders to monitor environmental conditions in real-time. From the interoperability point of view, environmental sensors may use different data formats and protocols, which can complicate integration with PCS. Nevertheless, implementing standardised data formats and communication protocols (e.g., MQTT, HTTP) ensures seamless data exchange between environmental sensors and PCS.

4.4.2 Interoperability within EU inland port systems

Interoperability is needed in case of data exchange or digital cooperation between different ports in the so-called EU inland port systems. As defined in Section 2.4, EU inland port systems encompass inland ports along the same waterway or river basin, or inland ports in the same region, at the same time cooperating between themselves and competing for the same cargoes. In this context, interoperability solutions between digital tools used in these ports can have a decisive role in enabling collaboration, coordination, and efficiency among inland ports, and especially among those inland ports participating in common transportation chains, such as ports along the Rhine River, which are served by feeder vessels transporting containers to/from, say, ARA (Antwerp-Rotterdam-Amsterdam) ports range.

The primary objective of interoperability of digital tools among ports of EU inland port systems, apart from facilitating collaboration, is to overcome the challenges that may arise due to fragmented digital systems and different data formats. Interoperability solutions aim at creating uniform digital ecosystem which could enable seamless data flow between different ports, terminals and other stakeholders spread across different ports. This is necessary because of the need to enable enhanced visibility, improve decision-making, and optimise resources. Promoting interoperability between digital tools can bring benefits in view of streamlined operations, reduced administrative workload, and improved competitiveness of inland waterway transport (IWT) sector as a whole.

Strategies for the implementation and improvement of interoperability that can be applied by EU inland port systems are discussed in Section 4.3. Additionally, when multi-port systems are concerned, interoperability solutions may include the integration of particular PCS, data sharing platforms and collaborative tools, with the purpose of enabling the real-time communication and collaboration between relevant stakeholders.

Minimum components, features, and architecture of interoperability solutions are the same as for the solutions applied for single ports.

Interoperability solutions for multiport systems can harmonise administrative processes, reduce paperwork and eliminate duplication of work, leading to cost savings and efficiency increases. Moreover, these multiport solutions can enhance the visibility and transparency of the supply chain, facilitating improved decision-making, allocation of resources and risk management.

Additionally, interoperability solutions for multiport systems improve connectivity and integration within the inland ports network, facilitating the increased use of shared resources, infrastructure, and services more efficiently. For example, interoperable PCS and TOS in various ports in the system enable seamless coordination of vessel movements, berth allocations and even cargo handling operations, thus optimising vessel turnaround times and port utilisation rates.

Through shared platforms and collaborative initiatives, ports in the EU inland port systems can exchange data on vessel schedules, cargo volumes and terminal capacities, thus allowing for more effective planning and resource allocation. For example, feeder vessels distributing containers from nearby seaports to inland ports located in their hinterland collaborate with inland ports to coordinate cargo handling and ensure smooth port calls. Similarly, inland port can collaborate to consolidate containers from various inland locations for onward delivery to nearby seaports, optimising container utilisation and reducing transit times.

One of the successful examples of shared platforms and collaborative initiatives is the RiverPorts Planning and Information System (RPIS).[85] RPIS was first launched in 2014 as a collaborative effort among the ports of Basel, Mulhouse, Weil am Rhein, Colmar-Neuf-Brisach, Strasbourg, Kehl, Karlsruhe, Mannheim, and Ludwigshafen. In a nutshell, RPIS unifies various port stakeholders along the Rhine, bypassing traditional barriers of companies, countries, and waterways. It allows seamless exchange of important data among included stakeholders and thus streamlines port operations. RPIS is, inter alia, the first barge reservation system for inland ports, which grew enough to be considered as the world's first multiport PCS. Through a neutral integrated service platform barge operators can reserve slots at multiple terminals along the Rhine, while terminals can smoothly handle slot reservation requests and quickly respond to barge operators. This results in fully optimised round-trip scheduling for barges. The system also informs users on barge positions in real-time, triggering warning in case of any delays. RPIS has numerous other functions, such as coordinating barge calls, data exchange and administration, visualisation, container management, customs modules, cargo information, etc. In the future, RPIS will incorporate novel digital technologies such as IoT, Big Data, Artificial Intelligence, Blockchain, etc.

For the handling of data coming from various sources and digital systems, RPIS relies on typical interoperability solutions such as middleware solutions, which are used to "translate" the communication between different tools. Middleware is responsible for functional mapping of incoming messages into the receivers "language" (data format).

4.4.3 Interoperability between EU inland ports and connecting EU seaports

Interoperability between digital tools in inland ports and connected seaports encompasses various aspects that ensure seamless communication, data exchange, and coordination among various systems used by different stakeholders.

Minimum components, features, and architecture of interoperability solutions are the same as for the solutions applied for single ports and for EU inland port systems. It is worth remembering that, technically, data exchange and integration functions require standardised data formats (e.g., XML, JSON, EDIFACT) to ensure that information can be easily interpreted and used by different systems, while standardised APIs are needed to enable different digital systems to communicate and share data efficiently. In addition, communication protocols (e.g., HTTP, MQTT) are needed to facilitate the transmission of data between various digital tools. It is also necessary to enable centralised and harmonised master data (e.g., vessel names, location codes) to reduce inconsistencies and errors across different systems. System compatibility is typically facilitated through middleware and Enterprise Service Bus (ESB). Middleware bridges the gap between different systems, ensuring compatibility and smooth data exchange, while ESB connects various applications and services, facilitating interoperability.

Strategies for the improvement of interoperability between digital tools and systems used in EU inland ports and connecting EU seaports are exactly the same as in the previous two cases – in single inland ports and in EU inland port systems.

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[85] https://rheinports.eu/en/

The integration of EU inland ports and connecting EU seaports is important for the establishment of seamless supply and transportation chain which involve multiple transport modes. When digitally integrated, inland ports and seaports form the backbone of the cohesive network which allows efficient mobility of goods "from source to sink", that is, from production sites to end consumers, using both maritime and inland waterway links. This integration between inland and seaports can be materialised through, for example, digital platforms in both inland and seaports. Integration of various digital tools and systems in both types of ports into digital platforms solves the interoperability issues, apart from the technical solutions described earlier in this Chapter. Digital platforms for data exchange facilitate real-time data exchange on cargo movements, vessel schedules and current or foreseen operational status of both seagoing and inland vessels. These platforms typically have user friendly interfaces and customisable dashboards, allowing users to customise their visualisation on the basis of their specific needs and preferences. APIs serve as the backbone of many digital platforms, allowing smooth integration of involved digital tools and applications. APIs allow port authorities, terminal operators, shipping lines, logistics providers and other stakeholders to perform real-time data exchange, take benefits from automated workflows, and reduce errors caused by manual data entry. Thanks to the standardised data formats and protocols, APIs ensure interoperability between different digital systems that are integrated in the platform. Through interoperability, stakeholders can have a holistic view of the supply chain, which, in turn, allows them to make more appropriate decisions and improve their overall operational efficiencies.

One of the important aspects of the cooperation between inland and seaports is the cargo tracking and intermodal connectivity. Digital technologies have a crucial role in enabling real-time cargo tracking, as well as smooth transitions between different modes of transportation, for example, from seagoing vessels into inland barges. One of the key technologies used for cargo tracking is the Internet of Things (IoT). IoT sensors can be placed in, for example, containers, trucks, and vessels, enabling monitoring of the cargo location, temperature, humidity, and other characteristics in real-time. Interoperable solutions "translate" the data collected by such IoT sensors and digital platforms display them as needed. Somewhat simpler solutions, where only the cargo location is needed, can be achieved with radio-frequency (RFID) technology (typically in the form of tags attached to cargo or vehicles). These RFID tags enable automatic identification and tracking throughout the supply chain. As cargo moves between inland ports and connected seaports, RFID readers can be installed at key checkpoints, allowing automatic capture, and recording of relevant data. This, in turn, provides real-time visibility into cargo movements. In this case too, if the RFID readers use different data formats (for reading, storing, and transmitting), various interoperability solutions can be applied in order to enable seamless data exchange.

In addition to digital platforms for information exchange, EU inland ports and connecting seaports can engage in joint development projects to test innovative solutions and battle common challenges. These projects may focus on developing new technologies, improving digital infrastructure, or standardise operational procedures with the aim of improving interoperability and efficiency.

One of such projects is the initiative of digital platform operators Portbase (operating digital platforms in the Port of Rotterdam) and RheinPorts (operating common digital platform for various inland ports along the Rhine River).[86] The two operators aim to optimise the flow of data between the seaports in the Netherlands and the inland ports on the Rhine. The Port of Rotterdam, Duisport (Port of Duisburg) and Port of Switzerland are supporting this project as shareholders and act as project promoters.

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86 https://container-news.com/platform-operators-launch-digital-sea-and-inland-port-networking-initiative/

The combination of the Portbase Port Community System (PCS) and the RheinPorts RPIS (RiverPorts Planning and Information System) improves efficiency and transparency along the supply chains from the seaport to the inland ports in the hinterland, and vice-versa. The project includes the seamless exchange of data, facilitating import and export process optimisation, improvements in planning and the simplification of data sharing with the relevant stakeholders. This resolves the issues in interoperability and data exchange along logistics chains, thus bringing an added value for carriers, terminals, ports, and all involved stakeholders. Apart from the collaboration between the inland ports along the Rhine and connecting seaport of Rotterdam, and between the operators of the two platforms, logistic operators along the supply chains also have their role by connecting with the platforms, performing data exchange, and thus creating added value with the services they offer. The overall objective of the participants in this initiative is to create a digital corridor, enabling smooth and secure data exchange, simplify procedures and increase operational efficiencies for inland shipping and involved ports. Test phase for this project is planned to be completed by the end of 2024, while gradual take-up is planned in 2025.[87]

4.4.4 Interoperability between inland ports and stakeholders' systems

Inland ports are not and cannot be viewed as isolated systems. Since they are important nodes of at least two different modes of transport, they involve numerous stakeholders, each of them using a variety of digital tools and systems to optimise their own operational processes and improve their own efficiency. External stakeholders (entities typically based outside physical port boundaries) include rail operators, trucking companies, logistic providers, multimodal transport providers, etc.

Rail transportation has a significant role in connecting inland ports to the rest of the transport and logistic network, facilitating the efficient mobility of goods between ports and inland destinations. Rail operators use a wide range of digital tools to manage their operations, including, for example, scheduling software, route optimisation tools and shipment tracking systems. All these systems ensure timely deliveries, minimise transit times and increase the overall efficiency of rail transport operations.

Trucking companies transport cargo between inland ports, distribution centres, and final destinations, having an important role especially in the last-mile transports. Trucking companies use digital tools such as electronic logging devices (ELD), GPS tracking systems, online booking platforms, fleet management software, route planning applications, etc.

Logistic providers coordinate movement of goods throughout the supply chain, from source to sink. This is a very complex and time-consuming process, and to manage it effectively, logistic providers use a wide range of digital tools and systems, such as warehouse management systems (WMS), transportation management systems (TMS), supply chain visibility platforms, etc. WMS enable logistic provides to optimise warehouse or storage yard operations, including inventory management, order fulfilment, and labour allocation. TMS coordinate the movement of goods across different modes of transport, including truck, rail, air, inland waterway, and sea, while supply chain visibility platforms provide real-time visibility of the status of shipments and inventory levels, enabling proactive decision-making and response to supply chain disruptions. The work of logistic providers is frequently interlinked with the work of multimodal transport providers, and, in many cases, it is performed within the same organisation. In such cases, logistic providers and/or multimodal transport providers use the supply chain visibility platforms, which are either the same or very similar to multimodal booking platforms, to book and track shipments across multiple transport modes. Using digital technologies such as cloud computing, APIs, and mobile applications, these platforms facilitate the booking process, optimise route planning and

[87] Ibid.

collaboration among individual transport providers, resulting in faster transit times, lower cost, and even lower environmental footprint of the entire supply chain.

From the technical point of view, interoperability between these digital tools and systems is achieved using the same strategies, technologies, and tools as in other categories of port systems.

All these digital tools and systems use different standards, data formats and communication protocols. As in the case of digital integration platforms of EU inland ports and connecting EU seaports, one of the options to overcome the interoperability issues, apart from the earlier described technical solutions and strategies, are the digital integration platforms. There is a large number of commercially available digital platforms integrating ports and stakeholders systems. Some of them are MyTerminal[88], NxtPort[89], Flexport[90], Shippeo[91], etc.

[88] https://myterminal.ect.nl
[89] https://nxtport.com
[90] https://www.flexport.com
[91] https://www.shippeo.com

5 Interoperability in practice – survey results

5.1 Overview

This chapter contains the results of the 2nd survey performed among port stakeholders (port authorities, port operators and port digital tools developers/manufacturers) in the period of April – May 2024. Part of the survey contained questions related to interoperability of digital tools in four categories of port systems (single ports, EU inland port systems, EU inland ports and connecting EU seaports, and inland ports and stakeholders' systems), and the processing of their results is in the core of this chapter. Questions were designed in such way to obtain an insight into the real-life issues of interoperability between digital tools in inland ports, as well as the types of interoperability solutions applied in all four categories of port systems.

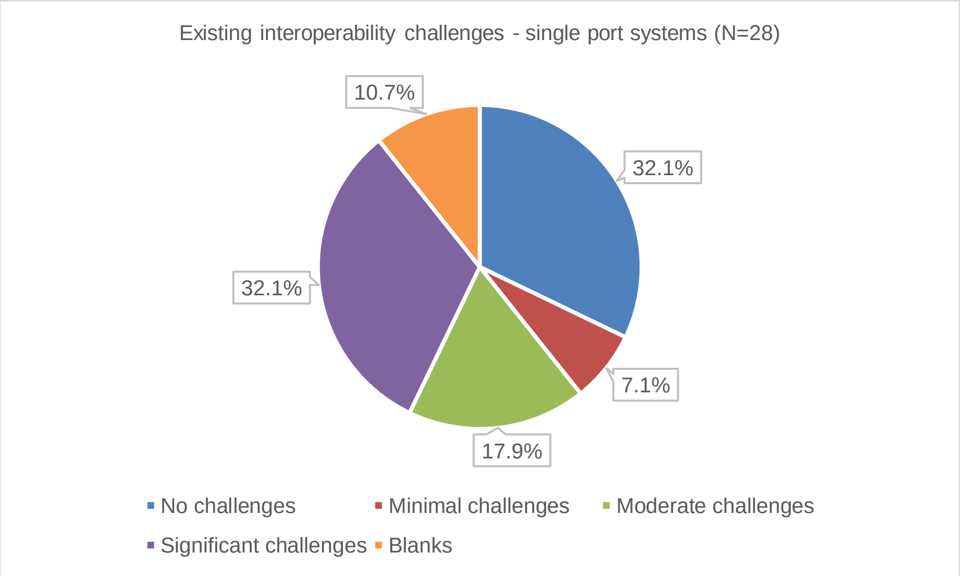
The total number of relevant respondents was 28, out of which 17 inland port authorities, 10 port operators and 1 developer/provider of digital tools for ports.

5.2 Results

5.2.1 Interoperability in single ports

Participating inland ports stakeholders demonstrated equally high degree of no interoperability challenges at all, and significant challenges, as shown in the following graph.

Figure 5-1: Interoperability challenges in single port systems

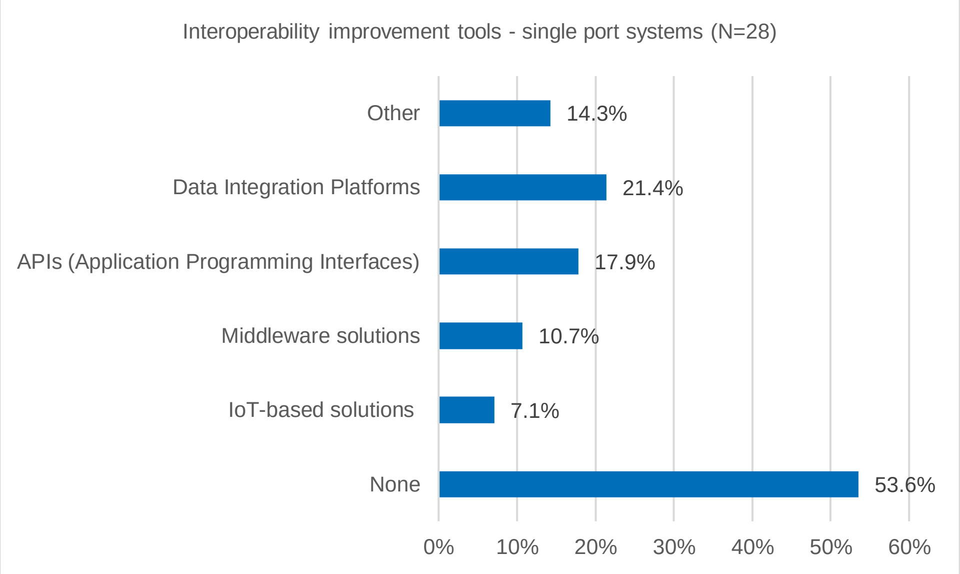


Source: Consortium

Remaining respondents reported minimal and moderate challenges with interoperability between digital tools in single port systems.

In view of applied types of interoperability solutions, the largest majority of ports reported that they do not deploy any interoperability solution, while among those who deploy some interoperability solutions the majority use various data integration platforms or APIs, immediately followed by users who deploy middleware solutions.

Figure 5-2: Types of interoperability solutions applied in inland ports



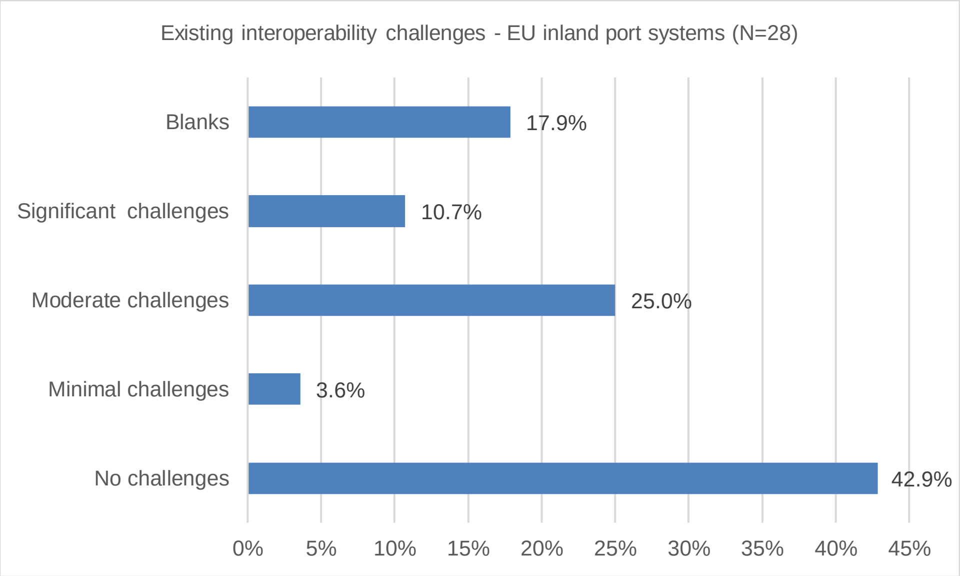
Source: Consortium

It is interesting to note that multiple ports reported the use of RiverPorts Planning and Information System (RPIS) as their preferred data integration platform for overcoming the challenges of interoperability.

5.2.2 Interoperability in EU inland port systems

The second category of port systems are EU inland port systems. These systems consist of, as defined in Section 2.4, ports that are located on the same waterway, or in the same river basin or region, that can cooperate and compete with one another at the same time. Whether they cooperate or compete for determined cargoes or users, certain information needs to be exchanged between ports and terminals in such systems, and this is where interoperability between various digital tools deployed in those ports takes place.

Figure 5-3: Interoperability challenges in EU inland port systems

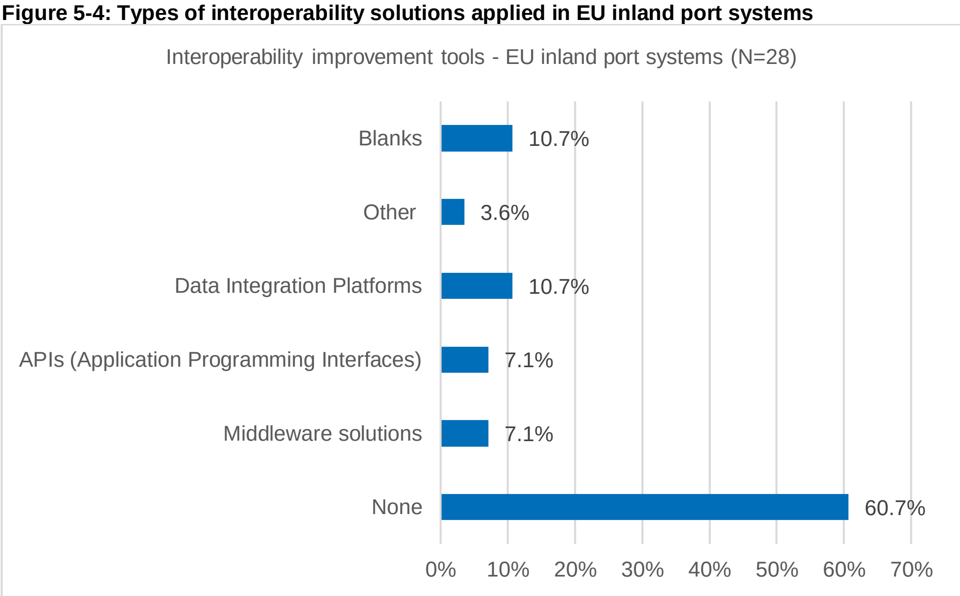


Source: Consortium

It can be seen from the above figure that EU inland port systems experience none or moderate interoperability challenges. However, it needs to be noted that there is a strong correlation between the respondents who reported that they use no interoperability solutions and those who reported no challenges.

When types of interoperability solutions are concerned, those ports that use at least one interoperability solution deploy primarily data integration platforms, followed by various middleware solutions and APIs. The largest share of ports in EU inland ports systems do not use any interoperability solution. This is typically a telltale sign of lower level of digitalisation of ports.

Figure 5-4: Types of interoperability solutions applied in EU inland port systems



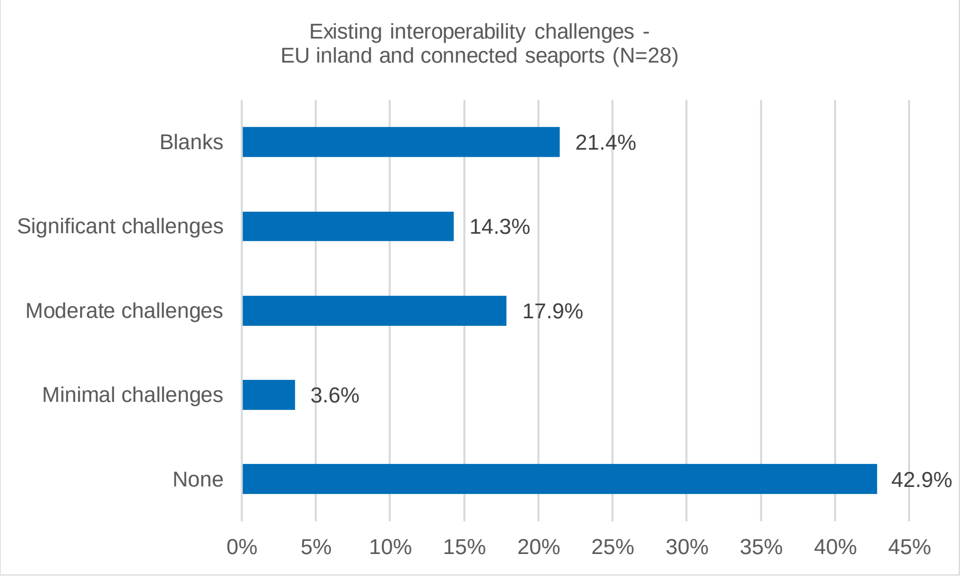
Source: Consortium

5.2.3 Interoperability between EU inland ports and connecting EU seaports

The third category of port systems are systems composed of EU inland ports and connecting EU seaports, such as ports along the Rhine River and seaports in the so-called ARA (Antwerp – Rotterdam – Amsterdam) range, or ports along the Danube River and the seaport of Constanta.

The situation with respect of experienced interoperability challenges in these port systems is depicted in the following figure:

Figure 5-5: Interoperability challenges in EU inland ports and connected EU seaports systems

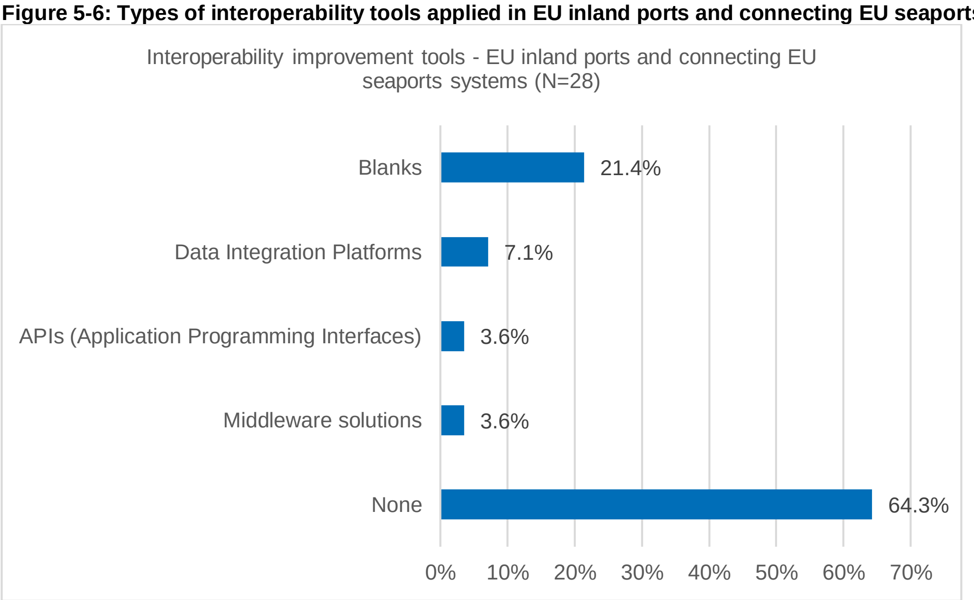


Source: Consortium

Of those ports which reported the presence of determined challenges in interoperability between their digital tools, approximately one third have moderate to significant challenges. The largest share of ports reported no interoperability challenges at all, which means that those ports have already applied some interoperability solutions/tools in their work, or their level of digitalisation is rather low.

Ports operating in the system of EU inland ports and connecting EU seaports apply primarily data integration platforms as preferred solutions for improvement of interoperability of their digital tools and operations in general.

Figure 5-6: Types of interoperability tools applied in EU inland ports and connecting EU seaports



Source: Consortium

As in previous cases, most ports do not apply any interoperability improvement tools since they either report no interoperability challenges or their level of digitalisation is relatively low to reach the levels of data exchange that would trigger interoperability issues.

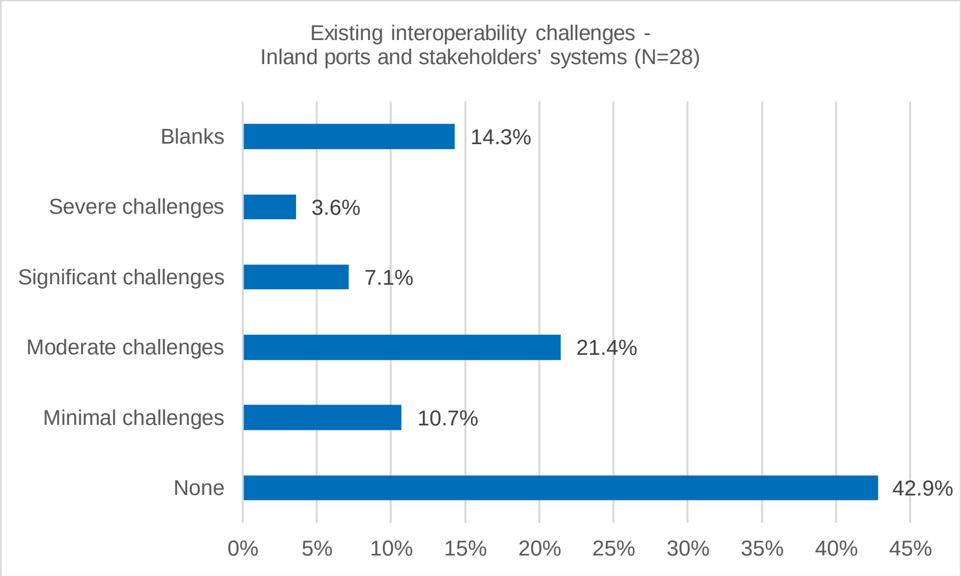
5.2.4 *Interoperability between inland ports and stakeholders' systems*

The fourth category of port systems under consideration consists of inland ports and their stakeholders, such as rail operators, trucking companies, logistic providers, multimodal transport providers, customs authorities, etc.

The integration of digital tools used in ports and in their stakeholders' organisations facilitates efficient coordination and information exchange throughout the entire supply chain involving these actors.

Responding ports which reported existing interoperability challenges between their digital tools and tools of their stakeholders state that they experience different levels of challenges, from minimal to severe challenges. The majority of those ports, however, report moderate challenges in interoperability, as illustrated in the below graph.

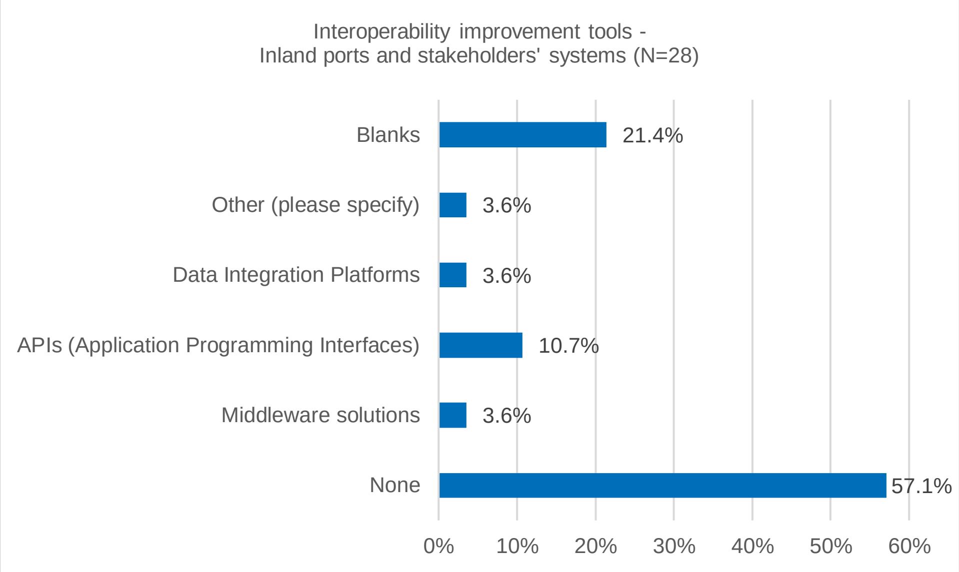
Figure 5-7: Interoperability challenges between inland ports and stakeholders' systems



Source: Consortium

Ports that apply some forms of interoperability solutions mostly apply APIs for the exchange of information and data with their stakeholders, as illustrated in the following figure:

Figure 5-8: Types of interoperability tools applied between inland ports and their stakeholders



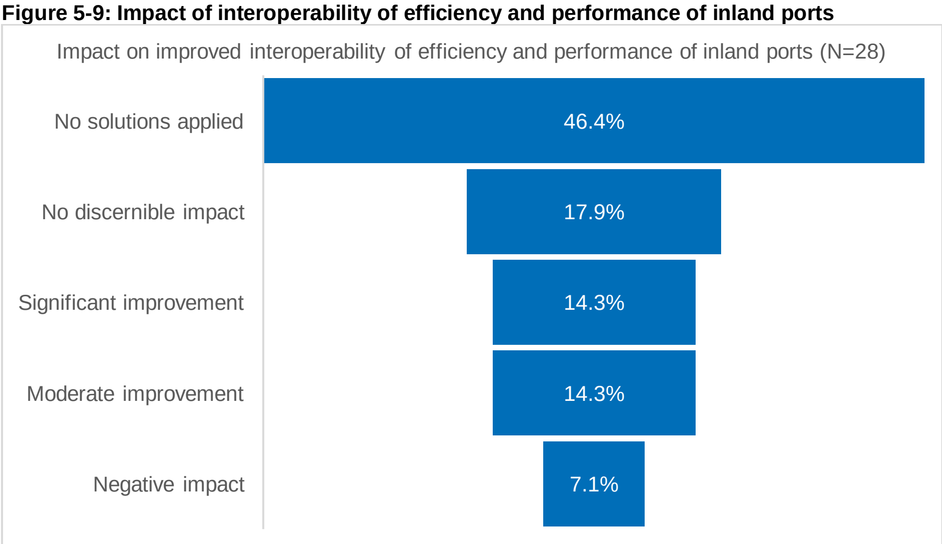
Source: Consortium

The largest majority of ports use no interoperability improvement tools, which can mean that the level of digital exchange of information and documents with their stakeholders is relatively low, or that the digital tools applied in inland ports and their stakeholders are already interoperable (e.g., they already exchange information using standardised data formats).

5.2.5 Impact of interoperability on ports' efficiency and performance

When asked to assess the impact of interoperability on ports' efficiency and performance, ports responding to the survey gave very peculiar answers, as shown in the following figure:

Figure 5-9: Impact of interoperability of efficiency and performance of inland ports



Source: Consortium

It is worth noting that the largest share of ports (17.9%) which applied some interoperability solutions for their digital tools reported no notable impact on their efficiency and/or performance. More surprisingly, 7.1% of ports reported even negative impact on overall efficiency and performance after applying some interoperability tools. Unfortunately, no explanations on such experience were available.

Some of the interesting comments (of those ports which experienced positive and not notable impacts) submitted along with the answers were the following:

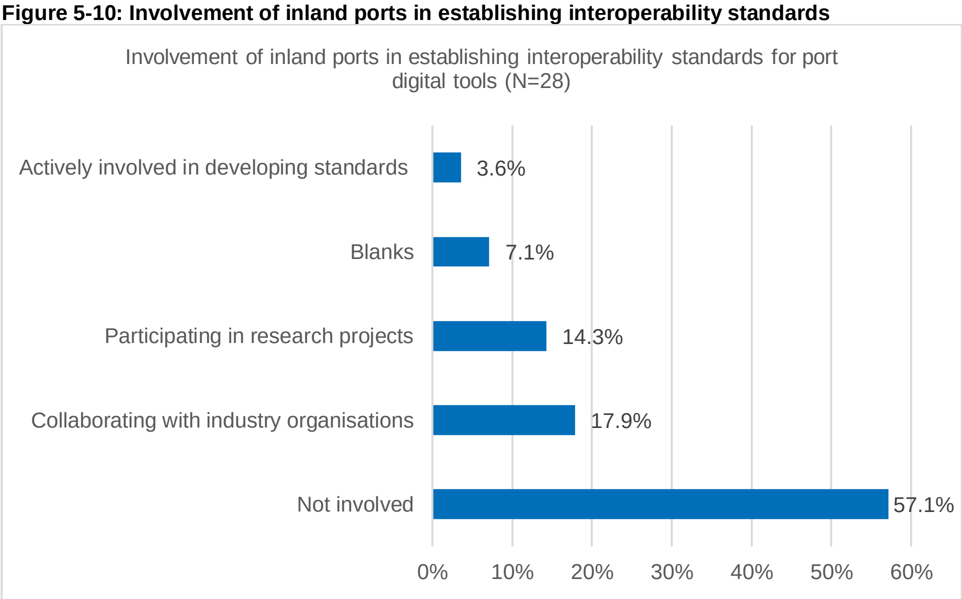
- "Due to the low shipping traffic and fewer ships unloading, an IT solution is not worthwhile".
- "Simpler and more efficient processing of transport data and invoicing".
- "Billing of shore fees gets easier".
- "Elimination of error sources, legal certainty, better statistical evaluations".
- "Streamlining of operational processes between different parties".

5.2.6 Involvement of ports in establishing interoperability standards for port digital tools

As explained in Section 4.3.1, common data standards are one of the crucial elements of strategies for the improvement of interoperability of digital tools. There is a number of international industry organisations having focus on establishing common data standards for ports, including inland ports, where ports can take part. Some of these organisations are: United Nations Centre for Trade Facilitation and Electronic Business (UN/CEFACT), European Port Community Systems Association (EPCSA), Digital Container Shipping Association (DCSA), etc. Other forms of involvement include participation in research projects and similar. Apart from common data standards, other interoperability standards involve, for example, blockchain standards, cybersecurity standards, single window systems, etc.

The figure below shows how inland ports are contributing to the development of interoperability standards.

Figure 5-10: Involvement of inland ports in establishing interoperability standards



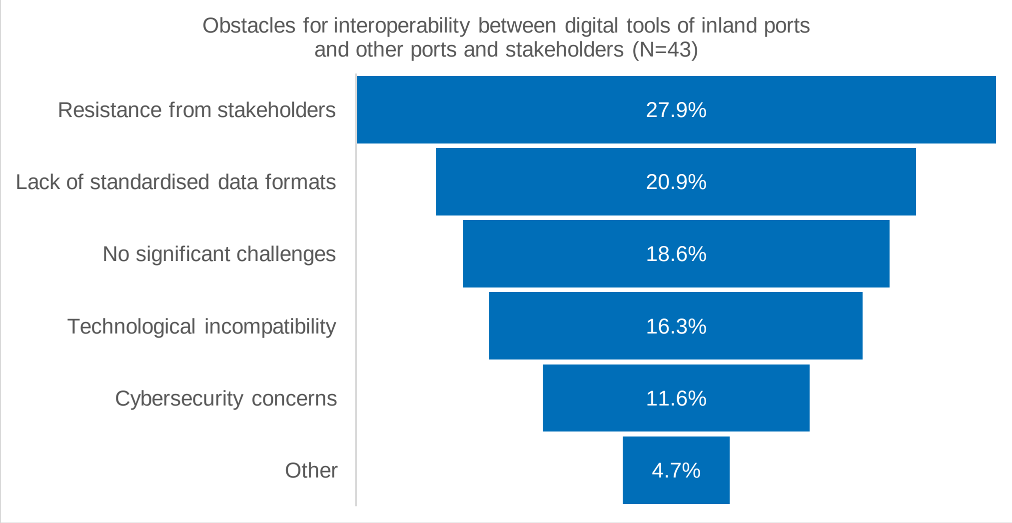
Source: Consortium

5.2.7 Obstacles for achieving interoperability between digital tools in ports and their stakeholders

Achieving interoperability between digital tools in ports and their stakeholders can be hindered by several obstacles, including reluctance to change and adopt new systems, inconsistent data structures that can make integration a very challenging task, differences in hardware and software platforms, risks related to data breaches and system vulnerabilities, etc.

The following figure contains responses from ports about their vision of obstacles for achieving interoperability.

Figure 5-11: Obstacles for interoperability between digital tools of inland ports and other ports and stakeholders



Source: Consortium

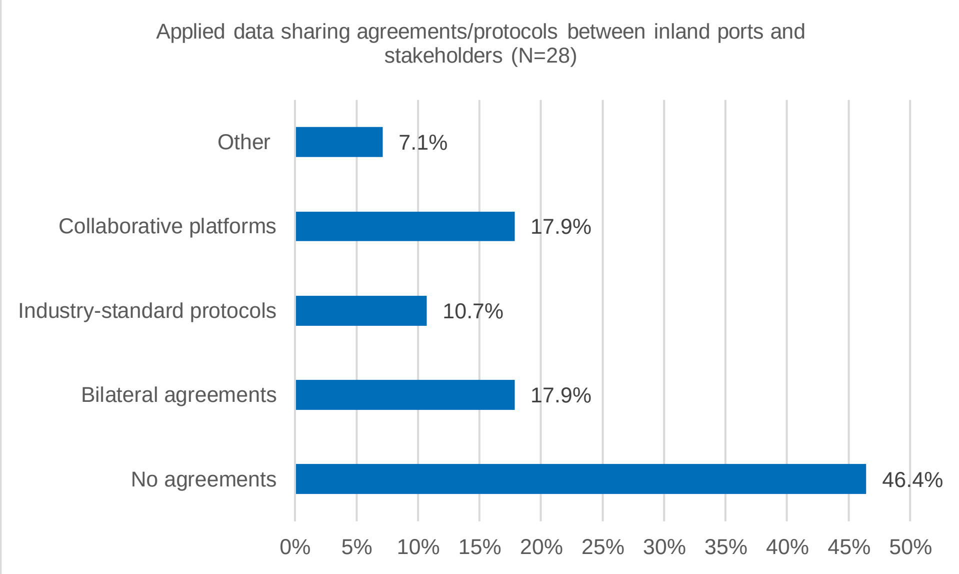
It is interesting to note that most ports emphasized resistance from stakeholders and lack of standardised data formats as their prime obstacles for achieving interoperability with their counterparts and other stakeholders. Multiple answers were allowed in the survey so that ports could select more than one answer, giving the total number of 43 responses.

5.2.8 Applied data sharing agreements and protocols between inland ports and stakeholders

Data sharing agreements and protocols between inland ports and stakeholders are very important for ensuring secure, efficient, and reliable exchange of data and information. These agreements and protocols set the stage for the commonly agreed rules, standards, and processes for data exchange, facilitating interoperability and collaboration among different stakeholders involved in port operations. They range from collaborative platforms, industry-standard protocols, APIs and web services, bilateral agreements, etc.

Below figure depicts the current situation in European inland ports regarding the most commonly used data sharing agreements and protocols used between inland ports and their stakeholders.

Figure 5-12: Applied data sharing agreements & protocols between inland ports and stakeholders



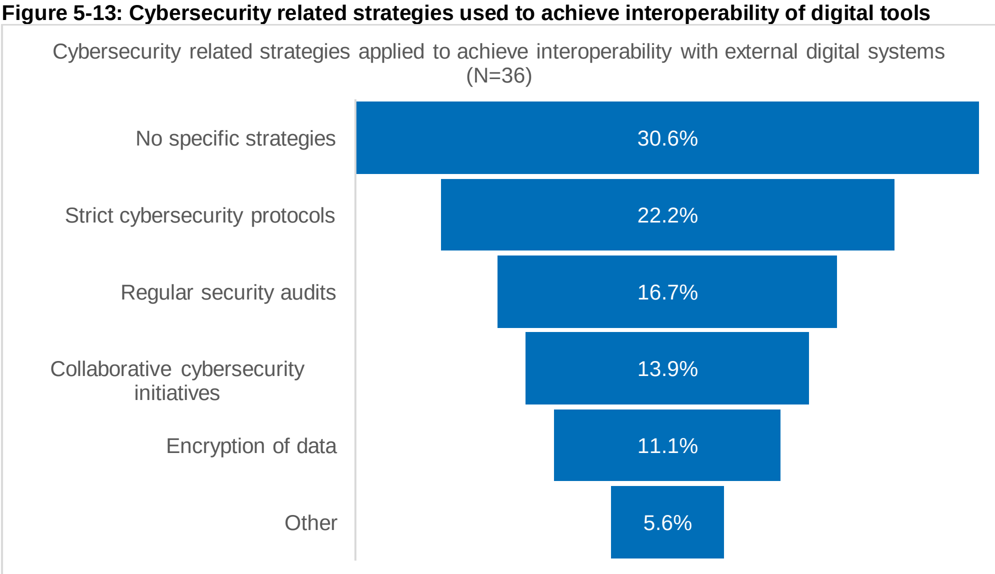
Source: Consortium

From the above figure, it can be seen that most port do not apply any data sharing agreements or protocols, while those ports that do apply some data sharing agreements and/or protocols use the widest possible variety of types of such agreements/protocols.

5.2.9 Cybersecurity related strategies applied in inland ports

The cybersecurity-related strategies applied to achieve interoperability between digital tools in the domain of inland ports and their stakeholders include, among others, strict cybersecurity protocols, regular security audits, collaborative cybersecurity initiatives, encryption of data, and many others.

Figure 5-13: Cybersecurity related strategies used to achieve interoperability of digital tools



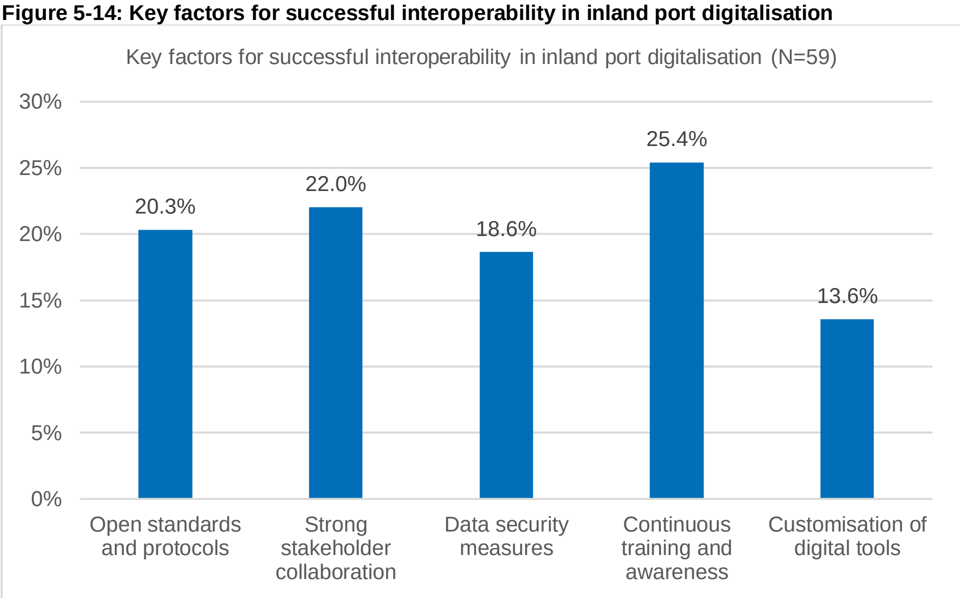
Source: Consortium

Above figure demonstrates that most of the ports that took part in the survey do not apply any specific strategies for cybersecurity (as they do not apply any specific interoperability solutions). On the contrary, inland ports that use some cybersecurity protocols mostly use strict cybersecurity protocols that include access control, authentication and authorisation, incidence response plans, and network security (e.g. firewalls, intrusion detection/prevention systems, etc.). These protocols are immediately followed by regular security audits, collaborative security initiatives (e.g. information sharing, joint training programs, standardisation efforts, etc.), encryption of data, and so on. Multiple answers were allowed in the survey so that ports could select more than one answer, giving the total number of 36 responses.

5.2.10 Key factors for successful interoperability in inland port digitalisation

During the survey, participants were asked to assess, based on their own experience, which factors for successful interoperability in inland port digitalisation would be the most important ones. Results are presented in the below figure.

Figure 5-14: Key factors for successful interoperability in inland port digitalisation



Source: Consortium

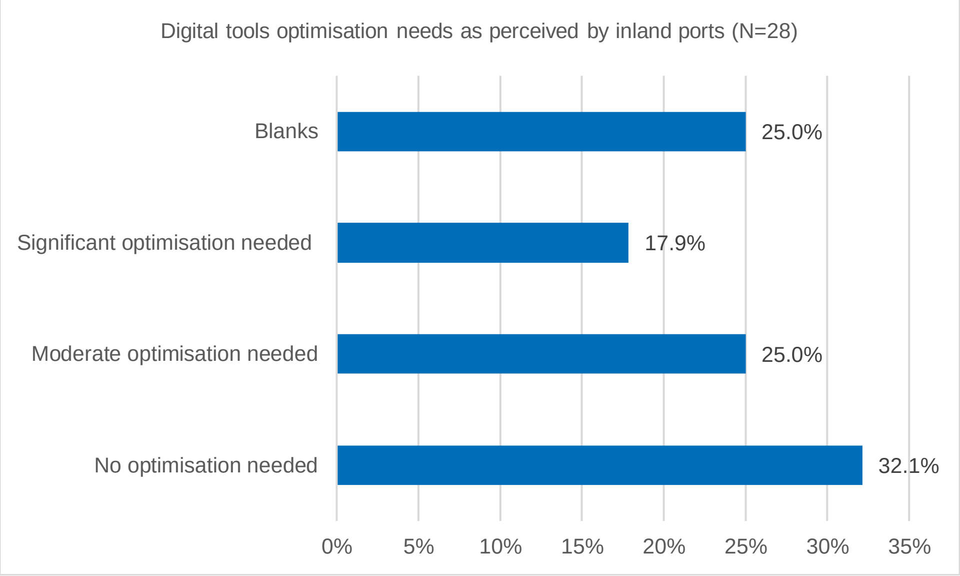
It is interesting to note that the participants were aware of the importance of awareness itself, combined with the continuous training which, based on the survey responses, is needed for inland ports. This factor is immediately followed by strong stakeholder collaboration, which is a good sign of the understanding of ports on the issue of collaboration with relevant stakeholders. Multiple answers were allowed in the survey so that ports could select more than one answer, giving the total number of 59 responses for this question.

5.2.11 Digital tools optimisation needs as perceived by inland ports

During the survey, the ports were asked to estimate the needs for the optimisation of existing digital tools. Most ports did not report optimisation needs, while those that did (nearly 38% of responding ports), reported optimisation needs in terms of upgrade to newer versions or to changed market needs. Some ports indicated the need for optimisation in view of end-to-end information chain, the use of digital waybills, digital recording of rail traffic handling in ports, optimisation for tracking of goods between all the ports, extended to rail traffic, etc.

The existing digital tools may not be performing to their full potential, possibly due to outdated technology, poor integration, or insufficient customisation. Since no detailed elaboration of the further optimisation needs could be obtained, the study teams assumes that the optimisation needs are likely caused by incomplete implementation, issues with data silos, where different digital tools do not communicate well with each other, leading to inefficiencies, scalability challenges, lack of training, etc.

Figure 5-15: Digital tools optimisation needs

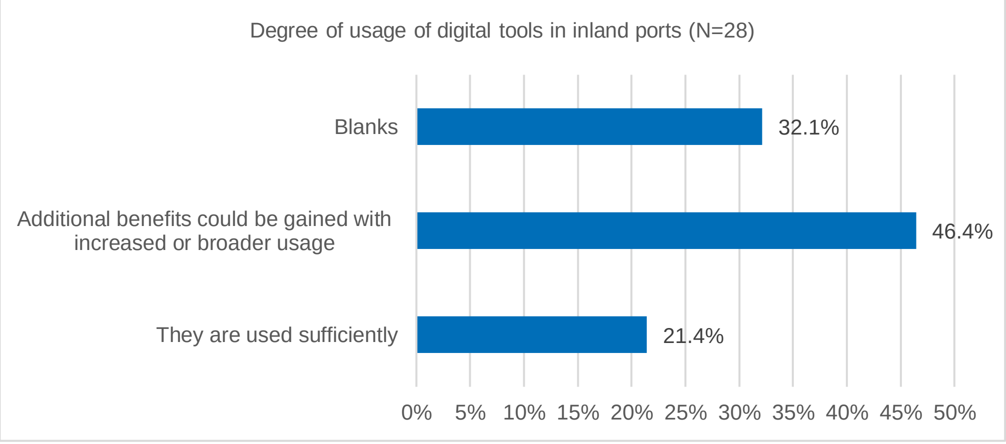


Source: Consortium

5.2.12 Degree of usage of digital tools in inland ports

It is interesting to note that almost half of the responding ports reported that additional benefits could be gained with increased or broader usage of digital tools in inland ports. This indicates that the awareness for the importance and usefulness of digital tools in ports is on the rise, and that ports and their stakeholders might have a potential gap in a technology usage that could be addressed. Port have recognised that digital tools proved themselves quite useful in improving operational efficiency, including logistic operations, reduced downtimes and streamlined processes. This type of response shows likely awareness that better data collection, analysis and use of data through digital tools could lead to better decision-making and optimised performance. Apart from the benefits experienced from the usage of digital tools, such as competitive advantage, cost savings or stakeholder communication, ports have likely recognised that digital tools can also be used to achieve positive environmental impact, in terms of monitoring and reducing of emissions, as well as energy consumption management.

Figure 5-16: Degree of usage of digital tools in inland ports

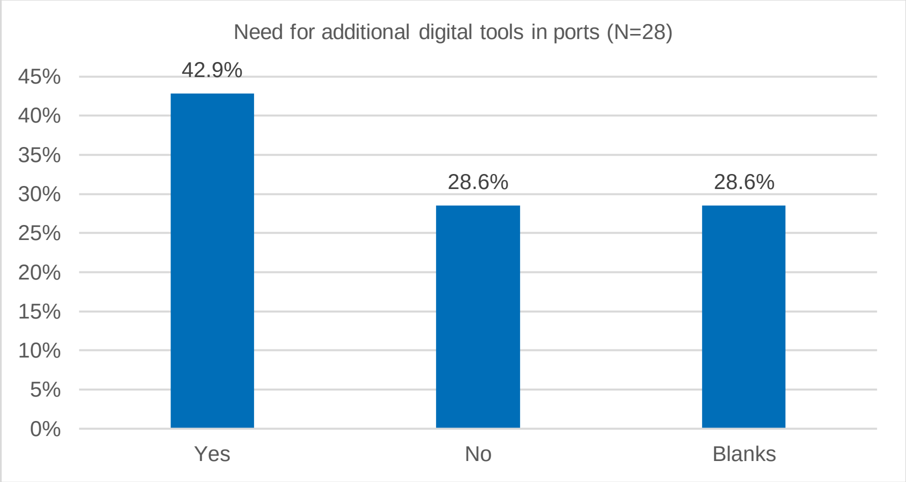


Source: Consortium

5.2.13 Need for additional digital tools in ports

In terms of the need for further digitalisation and additional digital tools in ports, nearly 43% of respondents indicated that they need additional tools in their ports.

Figure 5-17: Need for additional digital tools in inland ports



Source: Consortium

Responding ports indicated that the most frequent type of additional digital tools that are needed in inland ports are the following:

- data sharing tools,
- digital communication with customers,
- operations planning tools,
- energy management software,
- collaboration platform with all supply chain stakeholders,
- port fees, ship tracking, berth reservation, eco footprint calculations.

6 Upcoming projects, tools and technologies

6.1 Overview

This chapter aims to provide a brief overview of the latest tools, technologies and projects related to inland port digitalisation aimed at supporting inland ports with respect to process optimisation and systems integration as drivers of enhanced interoperability. Digitalisation of inland ports is driven by several key factors, encompassing, inter alia, the need to increase operational and administrative efficiency, reduce costs, turnaround times of vessels and vehicles in ports, and by the need to improve ports' environmental sustainability, primarily through the reduction of the environmental footprint of port activities.

Recognising the strategic importance of inland port digitalisation, numerous funding institutions and governmental bodies are supporting projects and initiatives boosting the innovations in this sector. Apart from the current study, on the European level, The European Commission, through its programs such as Horizon Europe, Interreg, and Connecting Europe Facility is actively supporting digitalisation efforts in many industries, including ports. For example, for the Horizon Europe projects, the CORDIS database (Community Research and Development Information Service)[92] is a valuable resource that provides comprehensive information on ongoing projects funded by the European Union. This platform, along with other databases and funding institutions, offers insights into the latest initiatives and collaborations aimed at enhancing the digital infrastructure of inland ports.

This chapter contains brief information on port digitalisation projects, without restricting itself only to the inland ports, primarily because of the fact that many digitalisation projects in seaports are also applicable to inland ports, with or without adapting to the conditions prevailing in inland ports. Moreover, seaports are much more visible transport nodes on the global level, being crucially important for the global economy and trade, and therefore receive much more attention, and, consequently, funds from both public and private sources, creating a myriad of projects. Apart from that, multimodal transport projects involving port digital solutions are also reviewed in this chapter.

In addition to the accessible databases of relevant digitalisation projects, desk research was also undertaken to search for such projects. Results of both methods are presented in continuation.

6.2 Horizon Europe Projects

6.2.1 AUTOSUP - Preparing the Ground for Autonomous Multimodal Supply Chains

This project was selected for funding under the HORIZON-CL5-2023-D6-01 call for proposals and was kicked off in June 2024 under the coordination of Inlecom Innovation Astuki Mi Kerdoskopiki Etaireia.

AUTOSUP will drive the industrial transition to seamless multimodal automatic freight transport and enhance the operation of hubs as nodes in a Physical Internet logistics network. A multidisciplinary team of 17 partners including four organisations engaging in the activities their ecosystems of Transport and Logistics stakeholders will:

[92] https://cordis.europa.eu

- Define automation requirements for seamless multimodal automatic freight transport.
- Empower stakeholders with an open, ready-to-use data-driven Decision Support System to help them implement and deploy automated processes and solutions and make strategic decisions about future investments. The systems will support undertaking feasibility studies via simulation to assess the efficiencies and impact of new solutions, whilst considering sustainability, financial and social impacts.
- Support the transition path to automation in two Living Hubs (Antwerp and Trieste ports), focusing on the link of the two large transport nodes with road corridors, rail, inland waterways and airports, covering 6 diverse use cases.
- Design new operational, governance and organisational change management models for autonomous logistics that incentivise cross-mode collaboration and reduce investment costs.
- Validate operational and cost efficiencies of solutions via feasibility analysis, impact assessment and the engagement of representative stakeholders.
- Establish a strategic and cohesive alliance and thematic working group for the alignment of multimodal automation adoption roadmaps across rail, road, aviation, waterborne and alternative innovative modes of transport and contribute to lowering automation adoption barriers through comprehensive transition guidelines, capacity-building sessions and policy recommendations.

AUTOSUP integrates social innovation practices in research to foster automation adoption and enhance safety, accounting for the workforce dynamics and skills needed for the transition to autonomous operations.[93]

The concept of an autonomous hub represents the first step towards entering the realm of 'Physical Internet logistics networks'. Within the AUTOSUP project, partners will develop concrete operational models for end-to-end intermodal logistics, focusing on the integration of the Port of Antwerp-Bruges and the Port of Trieste with road corridors, rail, inland waterways, and airports. These two ports will act as 'Living Hubs' (LH), where the operational and cost efficiency, as well as user acceptance of the automation solutions, will be validated across six use cases encompassing all existing and new modes of transport.

Innovative digitalisation and automation technologies are increasingly influencing operational logistics, presenting opportunities to introduce new business models and sustainable freight transport solutions. These innovations are essential for the transition towards the "Physical Internet," where full systems integration is vital. AUTOSUP will facilitate this transition by enhancing automation processes through a comprehensive approach, supporting strategic decisions about future investments.

AUTOSUP will define the automation requirements and empower transport and logistic stakeholders with an open, ready-to-use data-driven Decision Support System (DSS). This DSS will integrate customisable Digital Twin models of autonomous supply chains, aiding in the feasibility analysis and implementation of new operational, governance, and organisational change management models.

AUTOSUP will equip the Port of Antwerp-Bruges and the Port of Trieste to tackle the challenges of port automation and digitalisation directly. This project will provide a transition path towards AUTOnomous Multimodal SUPply Chains, targeting reduced investment and operational costs,

93 https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/how-to-participate/org-details/894512370/project/101147468/program/43108390/details

enhanced supply chain resilience, decreased transshipment time, reduced environmental impact, and advanced collaboration and interoperability.[94]

6.2.2 AUTOMOTIF – Automation Towards Multimodal Transportation and Integration of Freight

This project also started in June 2024, and it is planned to be completed until the end of May 2027. It was selected for funding within the HORIZON-CL5-2023-D6-01 call for proposals and it is coordinated by Erevnitiko Panepistmiako Institouto Systimation Epikoinonion Kai Ypologiston – Research University Institute of Communication and Computer Systems from Greece.

AutoMoTIF focuses on the development of strategies, business and governance models, regulatory recommendations and synergies that will enable the integration and interoperability of automated transport systems and solutions towards the operational automation of multimodal cargo flows and logistics supply chains in the intra-European network. It will list the gaps – both regulatory and technological – that are currently identified in automated transport technologies and logistics operations between modes and hubs through the analysis of automation demand and supply in multimodal transportation (users vs market).

AutoMoTIF follows an inclusive model to ensure that user and community needs are properly addressed, and innovations are aligned with their expectations. Use cases (UCs) and scenarios focus on real challenges and gaps in seamless automated logistics that will be simulated in real settings and different geographical locations. The results of the UCs will be used to set up a master scenario addressing the end-to-end delivery of goods using highest degree of automation possible. The outcomes from current practices will be analysed, leading to the assessment of benefits that can be gained by exploiting automated transport means to seamless multimodal automatic cargo transport and vice versa. These benefits will be defined and analysed based on their social, environmental, and economic impact, such as decreased emissions and congestion, improved working conditions and safety, as well as reduced logistics and freight transport costs, with the SSH aspects being a priority.

AutoMoTIF will contribute to the enhancement of synergies among sectors and stakeholders, following European priorities, strategic partnerships, such as Connected, Cooperative and Automated Mobility (CCAM), Zero Emission Waterborne Transport and EU Rail Joint Undertaking to ensure the transferability of expected outcomes.[95]

6.2.3 MULTIRELOAD - Port solutions for efficient, effective, and sustainable multimodality

MultiRELOAD is another project selected for funding under the HORIZON-CL5-2021-D6-01 call for proposals. It was initiated in September 2022 and is planned to last until the end of August 2025, coordinated by Duisburger Hafen Aktiengesellschaft from Germany.

MultiRELOAD project will enable European ports and freight nodes to actively drive the transition towards greenhouse gas emission-neutral shipping and wider multimodal mobility by 2025 with research and demonstration. Project activities will reduce freight transport by road by shifting it to inland waterways transport and rail and enhance the collaboration between different freight nodes in Europe to jointly test innovations and create favourable market conditions for multimodal freight transport solutions. MultiRELOAD will demonstrate solutions in three innovation areas: smart multimodal logistics, digital and automated multimodal nodes and corridors, and innovative

[94] https://inlecom.gr/autosup-preparing-the-ground-for-autonomous-multimodal-supply-chains/

[95] https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/how-to-participate/org-details/946059916/project/101147693/program/43108390/details

business models, with specific aims by 2025, mirroring the measures of the EU's Smart Mobility Strategy.

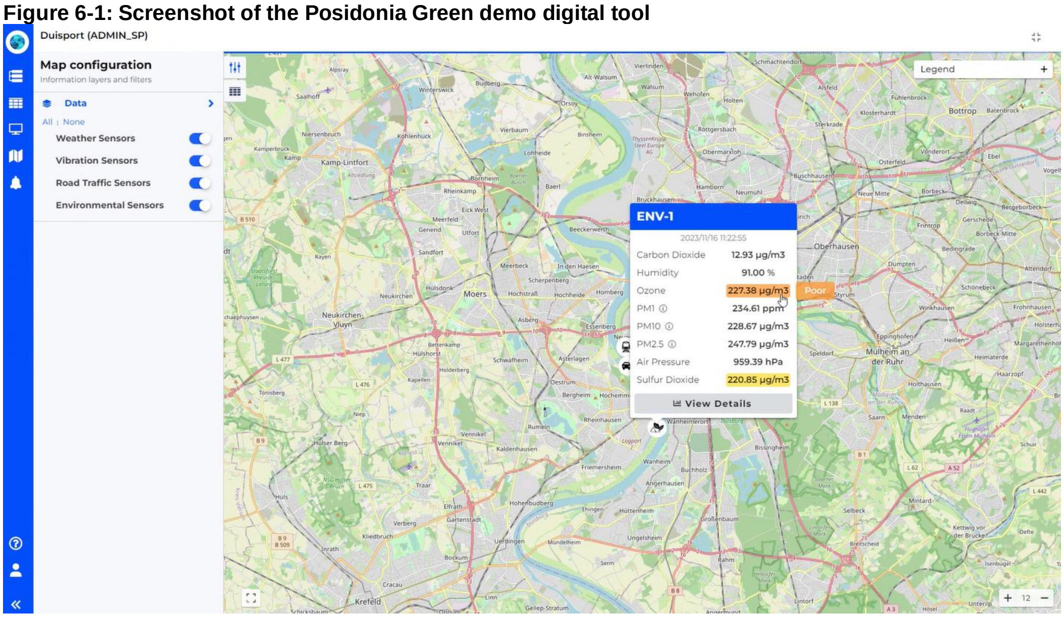
MultiRELOAD focusses on the specific role and challenges of inland ports as multimodal freight nodes in reaching Europe's greenhouse gas (GHG) reduction target of at least 55 % by 2030, thereby shifting a substantial part of the 75% of inland freight carried today by road in the EU to inland waterways and rail, and by increasing operational efficiency, safety, and reliability of existing infrastructures through digitalisation. Inland Ports are key for multimodal transport chains, both continental and maritime transport. Without efficient nodes in the hinterland multimodal transport is not possible. However, the constraints and barriers are much higher in inland ports (space, urbanisation, demand, investments) than in seaports. MultiRELOAD enhances the collaboration between different freight nodes in Europe to jointly test innovations and create favourable market conditions for multimodal freight transport solutions. MultiRELOAD will demonstrate solutions in three Innovation Areas with specific aims by 2025 – mirroring measures of the EU's Smart Mobility Strategy: A) Smart multimodal logistics: facilitate a shift from road to rail & IWT of 5%; B) Digital & Automated Multimodal Nodes and Corridors: increase operational efficiency by 20 % raise of handling capacity; C) Innovative business models: leading to an average cost reduction of freight transport by 10%. MultiRELOAD involves highly ambitious logistics hubs, including the multimodal node duisport (DE), Duisburg's highly ambitious port and the world's largest and most advanced trimodal inland hub terminal, and the trimodal nodes Ports of Vienna (AT) and Basel (CH). The project is backed up by additional funding & financing for better integration of the freight transport nodes into overall logistic chains of about 450 Mio. EUR. MultiRELOAD involves a total of 22 partners comprising of highly innovative technology, logistics and service providers, leading European research institutions and well-connected networks.[96]

From the digitalisation point of view, in line with the Digital Transport & Logistics Forum's (DTLF) digitalisation strategy, MultiRELOAD transforms intermodal freight nodes into interconnected data platforms to connect actors, physical and digital infrastructure, assets, resources, and services on three levels: terminal, node and corridor creating a truly integrated transport and logistics network. These innovations support the ongoing shift to multimodal service optimisation, creating door-to-door transparent supply chains by enabling tracking of freight locations and better and more efficient use of resources. Communication between the equipment thereby increases the use of standardised, interoperable intermodal transport units (ITUs) and IoT related services that are digitally accessible and bookable.[97]

One of the outputs of the project is a digital tool (Digital Twin) that will be able, inter alia, to monitor determined environmental KPIs which are collected via different sensors, such as weather sensors, vibration sensors, road traffic sensors, and environmental sensors, and to provide relevant data for decision-making. This digital tool (working title "Posidonia Green"), that is, its demo version for the Port of Duisburg, can present the historical data on environmental KPI, current values and even predictions (forecasts).

[96] https://cordis.europa.eu/project/id/101069796
[97] https://multireload.eu/knowledge-observatory/digital-and-automated-multimodal-nodes-and-corridors

Figure 6-1: Screenshot of the Posidonia Green demo digital tool



Source: Clemente & Torres, 2023.[98]

6.2.4 PIONEERS – Portable Innovation Open Network for Efficiency and Emissions Reduction Solutions

PIONEERS project was selected for funding within the H2020-LC-GD-2020 call for proposals. It was commenced in October 2021 and is planned to be completed by the end of September 2026. The project is coordinated by Haven van Antwerpen-Brugge (Port of Antwerp-Bruges) in Belgium.

PIONEERS will develop specific solutions to reduce carbon emissions in the sector, with the aim of transforming ports into green infrastructures by 2050. Solutions include the implementation of green port innovation demonstrations on clean energy production and supply, the deployment of electric, hydrogen and methanol vehicles, sustainable port design, modal shift and flows optimisation, and digital transformation through AI- and 5G-based digital platforms.

PIONEERS brings together four ports with different characteristics, but shared commitments towards meeting the Green Deal goals and Blue Growth socio-economic aims, in order to address the challenge for European ports of reducing GHG emissions while remaining competitive. In order to achieve these ambitions, the Ports of Antwerp, Barcelona, Venlo and Constanta will implement green port innovation demonstrations across four main pillars: clean energy production and supply, sustainable port design, modal shift and flows optimisation, and digital transformation. Actions include: renewable energy generation and deployment of electric, hydrogen and methanol vehicles; building and heating networks retrofit for energy efficiency and implementation of circular economy approaches in infrastructure works; together with deployment of digital platforms (utilising AI and 5G technologies) to promote modal shift of passengers and freight, ensure optimised vehicle, vessel and container movements and allocations, and facilitate vehicle automation. These demonstrations form integrated packages aligned with other linked activities of the ports and their neighbouring city communities. Forming an Open Innovation Network for exchange, the ports, technology and support partners will progress through project phases of innovation demonstration, scale-up and co-transferability. Rigorous innovation and transfer processes will address technology evaluation and business case development for exploitation, as well as creating the institutional, regulatory and financial frameworks for green ports to flourish from technical innovation pilots to

[98] Clemente, J.A., Torres, I. (2023). How to optimize Port Operation through a Digital Twin? Presentation presented at the Danube Ports Day, Vienna, 23.11.2023. Available at: https://www.prodanube.eu/images/20_2023-11-23_DPD_B4_digitaltwin_Torres_1_compressed.pdf

widespread solutions. These processes will inform and be undertaken in parallel with masterplan development and refinement, providing a Master Plan and roadmap for energy transition at the PIONEERS ports, and handbook to guide green port planning and implementation for different typologies of ports across Europe.[99]

One of the outputs of the project will be a Digital Twin (a demo version) designed to help port authorities with decision-making by providing insights into CO2 emissions, logistics, and people movement, developing a demo of three use cases that run the what-if scenario for vessel traffic, port emissions and train movement.[100]

The Port Digital Twin provides a comprehensive view of port processes and enables tracking of CO2 emissions across various domains. Using AI engines, it facilitates assessing the impact of different scenarios, aiding port authorities in formulating effective strategies to reduce CO2 emissions. The use cases are vessel traffic management, port emissions monitoring, and train movement. Each of these use cases will be developed in separate backend systems that connect to the Port of Antwerp-Bruges digital twin, APICA. The demonstrators have been created through a collaborative design process involving key stakeholders, with the aim of making the innovation transferable to other ports after the project completion.

- Use case 1: Vessel traffic. Thanks to the 30 minutes prediction of the vessel movements in the future, possible traffic conflicts can be avoided and, consequently, waiting time and congestions of vessels in the port can be reduced.
- Use case 2: Port emissions. By mapping the port CO2 emissions, the impact of abatement strategies can be put in perspective.
- Use case 3: Train movement. By creating E2E visibility of trains and wagons, flow management of trains can be optimised, and train process times can be reduced.[101]

6.2.5 CLARION – Climate Resilient Port Infrastructure

CLARION Project was kicked off on 7-8 May 2024 in Rotterdam and Delft, The Netherlands. Funded by the Horizon Europe Programme (Project 101147041 — CLARION) and coordinated by TU Delft, Faculty of Civil Engineering and Geosciences, the Geotechnical Engineering Section, CLARION is dedicated to enhancing the resilience and sustainability of European ports in the face of climate-related challenges, with a total EU budget of approximately 7 million euros.

Featuring the top-3 ports in Europe in terms of container throughput, namely Rotterdam, Antwerp/Bruges and Hamburg in the North Sea and the largest European port in the Black Sea, Constanta, CLARION will pursue ambitious objectives to increase the operational availability of port infrastructures during extreme events, reducing accidents caused by climate-related disruptions.

In line with the European Commission's EU Strategy on Adaptation to Climate Change and the European Green Deal, CLARION will support the modal shifts towards low-emission transport systems minimising environmental impact. During the project 10 pilot demonstrators will be conducted to test and deploy advanced technologies and strategies focusing on smart quay walls, monitoring system for the corrosion of port infrastructure, dredged sediment reuse, flood impact control, extreme weather forecasting and more, pushing the boundaries of current practices to future-proof port infrastructure also ensuring the transferability of results. The use of innovative

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99 https://cordis.europa.eu/project/id/101037564

100 https://pioneers-ports.eu/portfolio-item/port-digital-twin-enabling-tracking-of-co2-emissions/

101 https://pioneers-ports.eu/wp-content/uploads/2023/10/19.-Catchy-PIONEERS_Port-Digital-Twin-enabling-tracking-of-CO2-emissions-1.pdf

means (drones, sensors, AI, etc.) provided by CLARION through a pilot project implemented in the Port of Constanta, will be an important step in the port transformation and modernisation.[102] Therefore, the contribution of port digitalisation to the creation of climate resilient ports will be analysed in detail.

6.2.6 SEAMLESS - Safe, Efficient and Autonomous: Multimodal Library of European Shortsea and inland Solutions

Kicked off in January 2023, this project is coordinated by Ethnicon Metsovion Polytechnion, funded by EU Horizon Europe program, under the call HORIZON-CL5-2022-D5-01-05. It is planned to be completed by the end of December 2026.

From the digitalisation point of view, SEAMLESS aims at developing and adapting missing building blocks and enablers into a fully automated, economically viable, cost-effective, and resilient waterborne freight feeder loop service for Short Sea Shipping (SSS) and/or Inland Waterways Transport (IWT). Autonomous systems will be integrated to ensure safe, resilient, efficient, and environmentally friendly operation to shift road freight movements to hinterland waterways, while enhancing the performance of the TEN-T network. The service will be delivered 24/7 by a fleet of autonomous cargo shuttles, with humans-in-the-loop located in Remote Operation Centres (ROCs), which efficiently cooperate with automated and autonomous shore-side infrastructure and safely interact with conventional systems. The services will rely on a redesigned logistics system enabling seamless freight flows by minimising delays at intermodal nodes. A digital bird's eye view of the supply chain allows the exploitation of real-time information for planning optimisation and reconfiguration to support resilient logistics, incl. digitalised administrative procedures. The SEAMLESS building blocks will be verified and validated by conducting full-scale demonstrations in selected real-world scenarios. Transferability will be fully demonstrated in selected use cases that cover a wide range of transport applications and geographical regions throughout Europe. Based on a structured methodological framework evaluating sustainability criteria, they will act as guidance for the replication of the project results beyond the project scope and timespan. Novel business models will be thus developed and provide a framework for implementing the SEAMLESS service to minimise investment risk for first movers. Regulatory gaps and challenges related to autonomous vessel operation (e.g. social aspects) will be identified, and recommendations for policy makers to allow the smooth and safe deployment of fully automated services will be provided.[103]

One of the project's use cases will, inter alia, investigate the digital port call within the Port of Antwerp-Bruges, autonomous mooring, and automated container (un)loading through the quayside infrastructure.

6.2.7 EPICENTER - Enhanced Physical Internet-Compatible Earth-frieNdly freight Transportation answER

This project was recently closed (31 May 2024) and it was funded by the EU Horizon Europe program, under the call H2020-MG-2018-2019-2020 and coordinated by Port of Antwerp-Bruges.[104]

ePIcenter explored opportunities provided by AI, digitalisation, automation, and innovations in freight transport and handling technologies, creating powerful solutions to enable resilient, efficient and greener supply chains.

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102 https://www.hafen-hamburg.de/en/press/news/clarion-project-takes-the-lead-in-strengthening-european-ports-resilience/

103 https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/opportunities/projects-details/43108390/101096923/HORIZON?order=DESC&pageNumber=1&pageSize=50&sortBy=title&keywords=%20%20IWT%20and%20SSS&isExactMatch=true&programmePeriod=2021%20-%202027

104 https://cordis.europa.eu/project/id/861584

ePIcenter created an interoperable cloud-based ecosystem of user-friendly extensible Artificial Intelligence-based logistics software solutions and supporting methodologies. This ecosystem enabled all players in global trade and international authorities to cooperate with ports, logistics companies, and shippers, and to react in an agile way to volatile political and market changes, as well as major climate shifts impacting traditional freight routes.

This addressed the ever-increasing expectations of 21st century consumers for cheaper and more readily available goods and brought innovations in transport, such as hyperloops, autonomous/robotic systems, and new last-mile solutions. Additionally, it incorporated technological initiatives such as blockchain, increased digitalisation, single windows, EGNOS positional precision, and the Copernicus Earth Observation Programme.

The first aspect was visibility and collaboration, making the supply chains or logistic processes more transparent through cyber-secure data exchange and sharing.

The second aspect was optimisation, using new data and emerging technologies in a smart way, developing AI algorithms and simulation techniques that could optimise the real-life logistics and synchromodal planning processes end users faced daily.

In combination, the work on these two themes took a major step towards the Physical Internet concept and seamless sustainable global freight flows. By working closely with industry partners and dealing with real-life situations, the project delivered relevant applications that could easily be transferred to other end-users. Taking into account emerging technologies (e.g., hyperloop, automated vehicles) and trade routes (Silk route, Arctic route) in the simulation modules, the project also prepared for the future and challenges ahead. Ultimately, the project contributed to a more efficient and sustainable multimodal freight transport system and logistics.[105]

The ePIcenter applications represent actual solutions for real life challenges the industry is facing. To trial and test the ePIcenter solutions in real life conditions, 13 end-users were involved, representing major logistics and supply chain organisations, including sea and inland ports such as Port of Algeciras, Port of Antwerp, Port of Montreal and Duisport (Port of Duisburg).

The project also developed several demonstrators for transport links and nodes. The ePI-Link demonstrators focus on the integration of global and TEN-T networks by considering international trade routes from Asia and North America, and their linkage with the European transport system and logistics operations. They connect the physical, operational and digital (information) layers of supply chains and establish the optimisation of logistic operations by creating end-to-end visibility and the implementation of AI algorithms for (real-time) transport planning and scheduling on these trade lanes. The ePI-Node demonstrators focus on the validation of new logistics technologies and the optimisation of multimodal transfer zones (hubs, ports, terminals). They simulate the impact of new concepts such as Hyperloop and autonomous vehicles (Pods), modular containers (Connectainer), and innovative freight flow strategies operating in the logistics node of the future. This helps nodes to consider and compare different scenarios, understanding their impact and supporting (strategic) decision making.[106]

[105] https://epicenterproject.eu/about-the-project
[106] https://epicenterproject.eu/about-the-project/applications

6.3 Projects funded by other EU programs

6.3.1 Digital Port Platform

Digital Port Platform is a demonstration project funded by the European Space Agency (ESA). ESA Business Applications' Direct Negotiation (Call for proposals) is always open. Businesses from any sector can apply throughout the year, and the amount of funding may vary according to the activity.

The project is ongoing, but no details on the commencement and completion dates were available.[107]

The Digital Port Platform provides a set of connected applicative modules and services to improve the port's operations and lower their environmental impacts thanks to real-time situational awareness.

The Digital Port Platform is articulated around four services:

- A Predicted Time of Arrival applicative module
- A Water Quality Monitoring applicative module
- A Port Collaboration Service
- A Port Business Intelligence Service

The Digital Port Platform targets the Port Authorities, the Port or Terminal Operators, Port Master Office, and the Ship Managers to optimise their operational efficiency while reducing their impacts on the environment and more specifically to lower water pollution.

The Digital Port Platform is articulated with various modules & services:

- Predicted Time of Arrival applicative module
  - Accurate information about the incoming vessels (search, identify, blacklisted, exact position, etc…).
  - Estimation of full consumption and CO_2 emissions of specified vessels.
  - Accurate ETA prediction, comparison, share ETA among all stakeholders.
- Water Quality Monitoring applicative module
  - Monitoring of water quality from sensors (real-time and historical data) that can be moved to a strategic place.
  - Prediction to optimise dredging operations, know the incoming traffic, detect the marine oil pollution incident, and understand propagation.
  - Receive alerts in real-time and in case of incoming stormwater or flood risk.
  - Visualise a risk map of water areas threatened with pollution coming from the land.
- A Port Collaboration Service
  - Improve internal & external collaboration: Pin and label a pollution event, history of pollution observations, sharing of the blacklisted vessels.
- A Port Business Intelligence Service
  - News feed, per topics, and testimonials and use cases of port authorities' innovation.

The Digital Port Platform provides a holistic digital ecosystem dedicated to ports. This set of connected applicative modules and services is cloud-based, fully secured, and can be accessed through any device – to deliver:

- Comprehensive vision of operation and water environment
- Enhance collaboration

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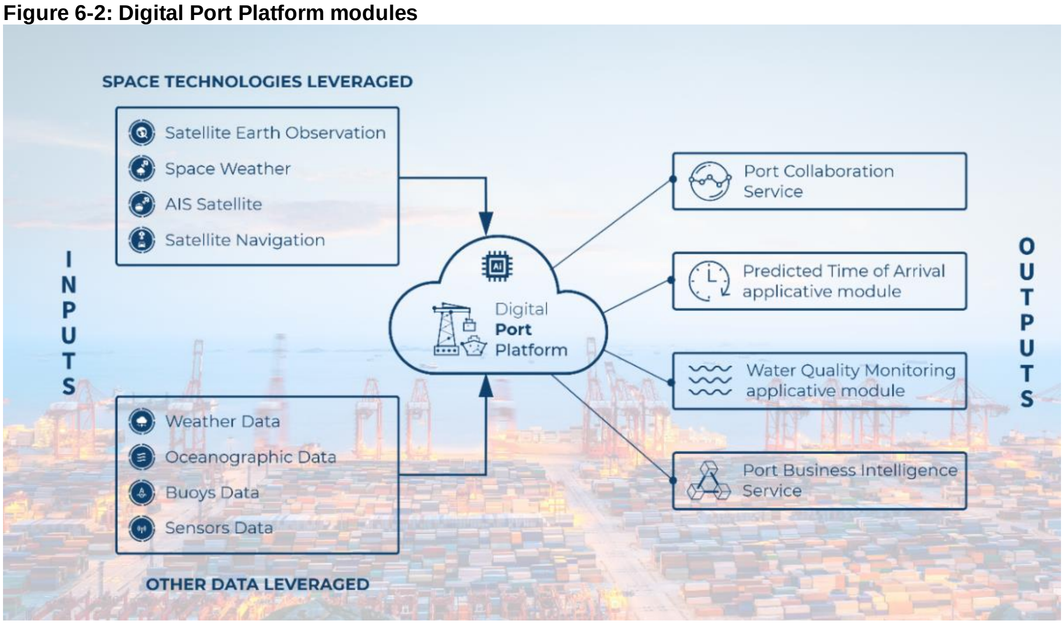
[107] https://business.esa.int/projects/digital-port-platform-0

- Increase awareness of innovation

The user can enhance Just in Time operations and Water monitoring thanks to Space Assets.

Figure 6-2: Digital Port Platform modules



Source: European Space Agency

6.3.2 Smart Port Maturity Model

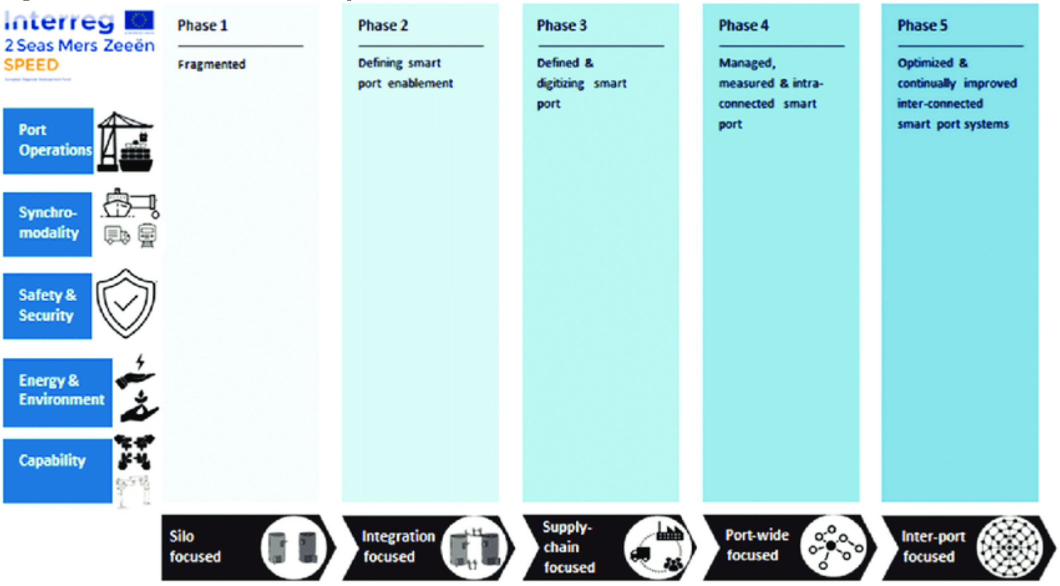
Smart Port Maturity Model^{TM}, or the Smart Port Barometer[108] was developed by Antwerp Management School as part of the SPEED (Smart Ports Entrepreneurial Ecosystem Development) Portal, a European Interreg 2 Seas project involving organisations from industry, public sector and academia in Belgium, France, The Netherlands, and the United Kingdom[109], aiming to build an ecosystem for smart port app development bridging the gap between the worlds of European ports and the nascent data science – IoT market. Although the project is not an “upcoming” one (lasted from January 2019 to June 2022), it is very interesting in terms of the possible capitalisation for the Deliverable 3.6 (Digitalisation Masterplan), and for this reason will be very briefly described here.

This self-assessment tool resulting from the project is designed for port and terminal organisations that are interested in developing a digitalisation roadmap and benchmarking themselves against their peers to understand their digital maturity in context. The outputs can help organisations to gain strategic focus and turn digital ambitions into a reality.

The Smart Port Maturity Model is represented in the following figure:

[108] https://www.nxtport-international.com/applications_apis/smart-port-barometer/
[109] https://www.smartportsalliance.org/diagnostics

Figure 6-3: The Smart Port Maturity Model



Source: Boullauazan, et.al.[110]

Boullauazan, et.al.[111] set up the two-dimensional model of smart port maturity, one dimension being the maturation path, and the other being the maturity domains. Each domain (port operations, synchromodality, safety and security, energy and environment, and capability) can be in five different phases of smart port maturity, along the maturation path (silo focused, integration focused, supply chain focused, port-wide focused, and inter-port focused).

The Smart Port Barometer, based on the Smart Port Maturity Model, is a free diagnostic tool designed to:

- Provide guidance for individual ports and terminals exploring digitalisation opportunities,
- Map the digital maturity of the organisation and benchmark against contemporaries,
- Provide a foundation for the prioritisation and development of digitalisation projects in port communities.

On the basis of a series of questions, port stakeholders can take the survey and self-assess their smart (digital) port maturity level and benchmark it against selected peers.

6.4 Other projects, tools, and technologies

6.4.1 *AutoPort*

Coordinate by Sintef Ocean, this project is financed by The Research Council of Norway and has a duration from 2023 to 2025.

Some larger ports around the world are undergoing a digital transformation towards the concept of Port 4.0, which involves the use of Industry 4.0 concepts like Internet of Things (IoT), big data, autonomy, AI, and augmented reality. These ports have implemented automated solutions to increase their efficiency, but this technology is rarely used in small-sized ports. Small-sized ports face a different type of challenge related to investment in flexible and automated infrastructure to accommodate for optimised and cost-efficient cargo handling across different types of goods.

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[110] Boullauazan, Y., Sys, C., and Vanelslander, T. (2022). Developing and demonstrating a maturity model for smart ports. *Maritime Policy & Management*, (50), 1-19. Available: https://doi.org/10.1080/03088839.2022.2074161

[111] Ibid.

The AutoPort project aims to address this challenge by using artificial intelligence (AI) and operational research (OR) to automate and optimise the planning process, execution of logistical operations, and the generation of work instructions for each automated equipment. The project will involve collaboration between several partners, including port operators, technology and equipment suppliers, autonomous ship operators, and transport authorities. The AutoPort Concept consists of three main levels: i) the operational level, where Operational Research and AI planning for equipment coordination and scheduling of tasks is used, ii) the tactical level, where management tactics for flow of goods and supervision of the autonomous and manually controlled port processes are developed in an operation centre, and iii) the strategic level, where intermodal transport chains are optimised in a long-term perspective and strategies for implementing autonomy and AI are developed. The project aims to achieve a modal shift from road to seaborne and rail transport in Norway, contributing to a more efficient, safer, and sustainable transport system. Secondly, the project aims to spur interest in business cases for the Norwegian maritime industry based on the AutoPort Concept.

The project involves collaboration between port operators, technology suppliers, autonomous ship operators, and transport authorities, with a focus on achieving a modal shift from road to seaborne and rail transport in Norway.[112]

6.4.2 XAIPRE - Explainable AI For Predictive Maintenance

The project XAIPre[113] is a project lead by the University of Leiden, The Netherlands, and is funded by The Dutch Research Council (NWO)[114], with the duration from 2022 to 2026. It aims to develop predictive maintenance system for the maritime industry using sensor technology and artificial intelligence. The project aims at developing Explainable Predictive Maintenance (XPdM) algorithms that do not only provide the engineers with a prediction but in addition, with 1) a risk analysis should the maintenance be delayed, 2) the criteria or indicators used to make that analysis. By providing more insight into the state of the machine, the engineers are empowered and given control over their maintenance process.

In practice, this might look like this: an engineer would usually maintain the equipment on an offshore location once a week, depending on vessel schedules. Should a vessel schedule suddenly change, the engineer can use the technology to assess the equipment’s current condition. The sensors in the machinery can provide data about key indicators, such as heat or friction, to the algorithm. The algorithm then provides the engineer with a risk analysis and the key indicators that influence this analysis (e.g. a component is heating up faster than is ideal).

XAIPre is focused on maintenance in the maritime industry (shipping and offshore platforms), but the solutions can be applied almost anywhere, with little or no adjustments to the specific equipment for which the maintenance is planned. Current maintenance concepts in the maritime industry are based on a fixed maintenance interval with a significant safety margin to minimise incidents. As a consequence, maintenance is always carried out too early making it one of the most inefficient industrial activities and most critical at the same time.

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[112] https://www.sintef.no/en/projects/2023/autoport-when-ai-optimizes-port-logistics-and-management/

[113] https://www.universiteitleiden.nl/en/research/research-projects/science/liacs-xaipre---explainable-ai-for-predictive-maintenance

[114] https://www.nwo.nl/en/researchprogrammes/smart_industry

6.4.3 Multiland

The Multiland solution is a resource dedicated to multimodal transport planning by HAROPA[115] (public company that acts like a joint port authority for the ports of Le Havre, Rouen and Paris), as of 2023. This latest-generation software program enables ports' customers to compare the economic and environmental benefits that can be obtained by choosing rail or river transportation from Seine Axis port facilities for journeys in France.[116]

6.4.4 Intelligent Deurganck Dock

This system deployed in the Port of Antwerp consists of software, cameras, and sensors. Upon their arrival at the port, ships are assigned a specific docking number on the quay. With cameras and sensors along the entire length of the quay, a check is performed to ensure each ship is docked at the correct quay. This maximises docking capacity and saves on costly ship manoeuvres in terms of time and money.[117]

6.4.5 STREAM5

The project is managed by the French IT company MGI.[118] The project aims to deploy an aggregation engine (business rules, pattern matching, machine learning) to enhance the data available to port actors.

At all points of the supply chain, particularly in ports, data is produced, consumed, and transformed in various formats using a multitude of technologies. Ports thus become "data hot spots," where the quality, heterogeneity, incompleteness, or desynchronisation of data can alter the smooth flow of information and goods. Inspired by the data pipeline concept promoted by UN/CEFACT, STREAM5 is a data enrichment platform (data alchemy) developed from research and development work carried out at the MGI Lab.

For illustration, for years, ship manifests have been electronically submitted to customs authorities and treated as lists of goods to be unloaded. STREAM5 enriches this document by applying multiple algorithmic processes, transforming it into an augmented multi-use document that can serve as a risk analysis support, a forecast of goods to be inspected, or a multimodal loading list.

Thus, for port and control authorities, it will be possible to optimise the management of facilities and control resources and improve the visibility of goods to be inspected. For terminal operators, shipping agents, customs brokers, and freight forwarders, it is possible to detect errors early, anticipate complex goods movements, enhance the attractiveness of short-sea shipping, and improve the connection with multimodal services. This project is developed in collaboration with the Grand Port Maritime de Marseille under the "French Smart Port in Med" initiative.[119]

6.4.6 Fluv'IOTe

Voies Navigables de France (VNF), along with various partners, launched the Fluv'iote and Eco-Piloting projects to advance the digital transition of inland waterways.

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115 https://www.haropaport.com/en/who-we-are
116 https://www.haropaport.com/en/innovation-goods-and-mobility
117 https://www.c-point.be/en/nieuws/deurganck-dock-gets-smart
118 https://www.mgi-ci5.com/en/the-mgi-innovation-lab/
119 https://www.vnf.fr/vnf/app/uploads/2022/06/T%C3%A9lechargez-les-articles-d%E2%80%99actualit%C3%A9s-sur-les-r%C3%A9sultats-des-%C3%A9tudes-pour-le-projet-FluvIOTe.zip

The Fluv'IOTe project involves a collaboration between Voies Navigables de France (VNF), the startup Antiote, Logistique Seine Normandie (LSN), and Normandie Maritime. The project aims to study and demonstrate the potential of the Internet of Things (IoT) around waterways, specifically in the Seine Valley. It was selected in the summer of 2020 as part of the call for expressions of interest "Ecological Transition and Economic Valorisation" launched by Agence de la transition écologique (ADEME)[120] in partnership with the regions of Normandy and Île-de-France under the Le Contrat de Plan Interrégional (CPIER) of the Seine Valley.

Specifically, the project aims to implement the tracking and geolocation of barges that are not equipped with AIS. It also targets to determine an optimal solution for monitoring parking areas for inland waterway barges used in the Grand Paris Express construction projects.[121]

6.4.7 DrakHAR

DrakHAR is the new Port Community System in the Port of Rouen, France. It is primarily aimed at the increase of interoperability with Le Havre and the players in the two port areas. Its first module, ECOPORT, a ship waste management module, was deployed in the beginning of 2023, while the new module for the ship fees and dues was deployed in September 2023.[122]

DrakHAR is a latest-generation PCS that uses new technologies and innovations from blockchain, IoT and big data to provide port operators improved control and management of their supply chains (improved fluidity and traceability).

This tool is the result of collaborative work between HAROPA PORT, the UPR - Union portuaire rouennaise, the USAAR - Union Syndicale de l'Armement et des Agents de Rouen - and software publisher SOGET.

It is planned to integrate new functionalities such as:

- environmental data (weather forecasts in particular),
- float monitoring,
- TIMAD (French acronym for "data processing for dangerous goods")[123] hazardous materials management.

The advanced technology of this PCS will be extended to Le Havre (by 2025) and is planned to be deployed in the Port of Paris to optimise the management of river calls in the Paris region.

6.4.8 Intelligent Transport System for inland waterway shipping in the Port of Hamburg

Hamburg Port Authority (HPA) is currently working on a scheme for developing an Intelligent Transport System (ITS) strategy for inland waterway shipping in Hamburg. This aims to optimise data interchange for inland waterway vessel services. Traffic data for all the players in the transport chain could in future flow into the system: Schedule and cargo data for inland waterway craft, terminal/lock/bridge availability, Elbe water levels and other current traffic data from the Harbourmaster's Office and the Nautical Centre. The project aims to optimise availability of data for inland waterway shipping in the Port of Hamburg, to enhance the reliability and calculability of transport processes, and to boost the utilisation and efficiency of transport infrastructure. In

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120 https://www.ademe.fr
121 https://www.lejournaldelaxeseine.fr/fluviote-liot-au-service-des-activites-fluviales/
122 https://www.haropaport.com/en/news/drakhars-rolling-out-rouen
123 https://www.haropaport.com/en/innovation-goods-and-mobility

addition, the ITS will reduce costs for users and improve traffic safety for inland waterway vessels. Data interchange between all players in the transport chain would be paperless, simplified and accelerated. Among other features, this will enable inland waterway skippers and terminals to react more flexibly to non-scheduled delays or changes. Connecting this system to the smartPORT logistics (SPL)[124] project will make the entire transport chain more transparent and efficient, with inland waterway shipping incorporated as well. A first pilot project to detect berth occupancy and inland waterway vessel arrivals in the Port of Hamburg will commence in 2025.[125]

[124] https://www.hamburg-port-authority.de/en/hpa-360/smartport
[125] https://www.hafen-hamburg.de/en/transportation/inland-waterways/

7 Conclusions and key findings

This report explored the optimisation and interoperability aspects of inland port digitalisation, and examined the latest tools, technologies, and projects aimed at, inter alia, improving the optimisation and integration of digital tools across different port systems. The report reveals that the digital transformation of inland ports is not just a simple technological upgrade, but also a strategic imperative driven by the quest for achieving higher operational efficiency, cost reduction, and environmental sustainability, reaching far beyond the ports boundaries. Joint efforts of various stakeholders, including funding institutions, governmental bodies, and private sector emphasize the importance of achieving optimisation, interoperability, and integration of digital tools not only in the domain of ports, but also in the broader context of supply chains.

The analysis of optimisation and interoperability aspects has shown that while there are significant challenges to achieving full digital interoperability, the potential benefits far outweigh these challenges. Study team's efforts delivered numerous strategies for achieving and improving interoperability of digital tools of different port systems. Research was backed by insights from the real-life situations encountered in inland ports, obtained from the survey that was recently completed.

The continuous support from programs such as Horizon Europe, Interreg, and Connecting Europe Facility reflects a firm commitment of the European Commission to advancing the agenda of digitalisation as one of the tools for achieving the objectives of the European Green Deal. In addition to that, the digitalisation experiences from seaports, being pioneers in digitalisation, serve as an important incubator of ideas and transferable solutions for inland ports.

As an outlook into the future, the experiences so far demonstrated that the journey towards the full digitalisation requires continuous legislative and financial support, significant investments, careful strategic planning, and, equally important, minds opened for new technologies. Further evolution of digital tools in ports, including their improved interoperability with other digital technologies, will not only improve ports' operational capability and efficiency, but will also improve their environmental performance. Findings and initiatives discussed in this report can provide a solid foundations for further innovations and collaborations in the digitalisation and integration processes.

The strategic initiatives and collaborative projects presented in this report demonstrate considerable efforts to address the complexities of interoperability and to harvest the benefits of digitalisation for competitive advantage and environmental sustainability. These initiatives and projects are important for generating further innovations in digitalisation and in digital interoperability, all having the same goal of improving the efficiency of port systems and contributing to the unhindered integration of various digital tools throughout the supply chains.

In conclusion, the digitalisation of inland ports itself, as well as their high interoperability with other digital systems in ports and across the supply chain, represents a fundamental step towards a more integrated and efficient logistics network. This report is intended to serve as a testimony to the progress made so far and as a booster for continued efforts in the digital transformation process.

In continuation, the study team synthesise the key findings and key takeaways from this report:

Key findings:

- Process optimisation and efficiency: it has been proven that digitalisation can improve operational efficiency in inland ports, modernise administrative and operational processes, optimising the port stay for both vessels and vehicles, and reduces costs.
- Environmental sustainability: digitalisation itself demonstrably contributes to the reduction of environmental footprint of port operations, as it optimises the movements of vessels, vehicles and cargo handling equipment in ports, resulting in comparatively lower fuel consumption and consequently lower emissions; moreover, integration of digital tools improves these benefits even more since it increases the efficiency of the entire port systems.
- Interoperability: achieving interoperability of digital tools between various port systems is very important. Interoperability enables unhindered integration and data exchange between various digital tools, which is of utmost importance for the optimisation of port operations and enhancing collaboration between stakeholders.
- Strategies for improved interoperability: a myriad of technological and organisational strategies are available to ports and other stakeholders to use them in order to achieve or improve interoperability between different digital tools. These strategies include, inter alia, the use of common data standards, various middleware solutions, data integration platforms, cloud-based solutions, data governance practices, etc.
- Interoperability issues in European ports: survey demonstrated that interoperability of digital tools in various port systems is considered very differently, and that this depends mostly on the level of digitalisation of ports taking part in the survey. For example, of those ports which reported the use of some interoperability solutions, almost half of them reported moderate to significant improvement in operational efficiency and performance.
- New projects and technologies: a selected cross-cut of ongoing projects related to digitalisation of ports, including integration and interoperability aspects, demonstrated that ports are very much aware of the importance of further digitalisation and integration across supply chains (interoperability being the key to such integration of digital tools), and that they are developing new tools and technologies to advance the digitalisation of ports and their integration with other actors in the supply chains.

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