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Enhancing digital railway automation: Lessons from the Port of Trieste in Italy

Irina Di Ruocco [1]*, Marco Mazzarino[2]

[1]*Department of Economics, Mathematics and Statistics, University of Trieste, Via Alfonso Valerio, 4/1, 34127 Trieste, Italy*
[2]*Department of Architecture and Arts, Università IUAV of Venice, Ca' Tron, Santa Croce 1957, 30135, Venice, Italy*

Abstract

This paper investigates how smart technologies enhance efficiency, reliability, and sustainability in freight rail-port operations. Focusing on the Port of Trieste, the study applies a Digital Capability Twin (DCT) framework to model and compare the current state ("As-Is") with a future optimized scenario ("To-Be"). The research addresses two core questions: (1) how digital automation improves rail operations in intermodal hubs, and (2) whether the Trieste model can be transferred to other EU ports. The methodology includes a stakeholder analysis and the definition of key performance indicators (KPIs) to assess economic, environmental, and operational impacts. Results highlight substantial reductions in wagon downtime, increased asset availability, and improved reliability of terminal processes. The DCT approach supports strategic planning and risk mitigation by enabling simulation-based policy and investment evaluation. The study contributes to the evolving discourse on smart ports and railway digital transformation within European logistics corridors.

Keywords: Smart Port Innovation, Freight Transport Efficiency, Digital Capability Assessment.

1. Introduction

Freight rail systems play a strategic role in modern port ecosystems, acting as critical connectors between seaports and hinterlands and enhancing supply chain performance (Lam and Yap, 2011). Despite this, many European port-rail networks remain constrained by outdated maintenance practices, limited digitalisation, and infrastructure congestion (Notteboom and Rodrigue, 2008). Recent research has increasingly emphasised the transformative role of automation, digitalisation, and big data in enhancing port-hinterland connectivity and regional logistics systems (Di Ruocco and Mazzarino, 2025), particularly across the Adriatic and South-Eastern Europe, e.g. the studies conducted by Mazzarino et al. (2022a, b), Braidotti et al. (2020), Mazzarino et al. (2019), Borruso et al. (2021), and those by Caramuta et al. (2018, 2021, 2024) investigating the port of Trieste.

* Corresponding author: Irina Di Ruocco (irina.diruocco@deams.units.it)

Traditional maintenance approaches, largely reactive and manual, contribute to unplanned downtime, higher operational costs, and suboptimal resource utilisation. In response, emerging technologies—Predictive Maintenance (PM), the Internet of Things (IoT), and Digital Twins (DT)—are reshaping the management of port railway systems (Gerlach et al., 2021). These innovations enable real-time monitoring, predictive analytics, and proactive interventions (Henríquez et al., 2022), aligning with the Smart Port 4.0 paradigm that prioritises automation, sustainability, and resilience (H-Nia et al., 2023). Evidence from leading ports such as Rotterdam and Hamburg shows downtime reductions of up to 50%, maintenance cost savings of 30%, and asset lifespan increases of 15% (Moya et al., 2023). Furthermore, studies have reported 12% gains in energy efficiency and CO_2 emission reductions of 15% (Casper van der Woude, 2021).

To analyse this transformation, the Dynamic Capabilities Theory (DCT), originally developed by Teece et al. (1997), provides a valuable framework to describe how organisations sense opportunities, seize resources, and transform processes in response to environmental change.

However, its application remains limited in the specific context of railway-port integration and the digital transformation of freight system. This gap is particularly relevant in Southern Europe, where the adoption of smart rail-port solutions lags behind that of Northern hubs. Trieste represents a particularly relevant case in the national panorama: the railway mode plays a central role in port logistics, with a share of rail traffic exceeding 50% recorded in 2023[1]. Despite these results, critical issues persist linked to the aging of the wagon fleet, the fragmentation of maintenance systems and the still limited level of automation. As a pilot site within the AUTOSUP project[2], Trieste offers a fertile ground to investigate how PM technologies, aligned with DCT, can drive sustainable, resilient logistics innovation.

This paper addresses two core questions:

RQ1 How can predictive maintenance enhance sustainability and performance in port-based rail systems? and,

RQ2 What is the role of dynamic capabilities in guiding the digital transformation of Trieste's freight rail infrastructure?.

The contribution lies in applying DCT to Italy's rail freight sector and demonstrating how PM aligns logistics operations with Smart Port 4.0 goals.

The remainder of the paper is structured as follows: after this Introduction, Section 2 reviews the literature; Section 3 presents the methodology; Section 4 discusses results and policy recommendation; Section 5describes the conclusion.

2. Literature background

Recent literature highlights the transformative impact of digital innovation on port development, shifting attention from traditional metrics (e.g. quay length, crane capacity) to advanced technologies that redefine port ecosystems (Rodrigue et al., 2022). Smart

[1] https://www.transportevents.com/presentations/constanta2024/PortTrieste.pdf?

[2] AUTOSUP is a European project that supports the progressive automation and digitalization of multimodal freight hubs, addressing fragmentation and inefficiencies across logistics systems. It aims to enhance the readiness of Physical Internet (PI) nodes by increasing automation, improving digital connectivity, and fostering inter-hub collaboration. Through Digital Twin models and a data-driven Decision Support System, AUTOSUP provides a strategic framework to optimise logistics operations from technological, regulatory, and governance perspectives.

ports—labelled "Port 4.0"—increasingly adopt Industry 4.0 tools like IoT, big data analytics, blockchain, and Predictive Maintenance (PM) to automate operations, optimise logistics, and promote sustainability (Durán and Córdova, 2015). Among these technologies, PM plays a central role by enabling proactive maintenance strategies, reducing downtime, and improving asset efficiency (Moya et al., 2023).

These advancements support a triple bottom line approach that balances economic growth, social inclusion, and environmental responsibility (Benamara et al., 2019). Since ports are critical hubs in multimodal supply chains, their competitiveness increasingly depends on hinterland connectivity and seamless integration of land transport. Strategic digitalisation and collaborative governance are thus key to navigating complex, dynamic environments (Notteboom and Rodrigue, 2008).

Dynamic Capabilities Theory (DCT), introduced by Teece et al. (1997), offers a valuable framework for understanding how ports can adapt to evolving contexts by sensing opportunities, seizing resources, and transforming operations. This theory has been widely applied to the shipping industry and port innovation (Henríquez et al., 2022), providing a flexible model for integrating new technologies while improving sustainability and resilience. However, DCT remains underexplored in the specific context of railway-port integration. Most research focuses on maritime digitalisation or predictive maintenance for rolling stock, but few studies examine their intersection within freight rail systems and port ecosystems—particularly in Southern Europe (dos Santos and Pereira, 2021). Recent literature on PM in the railway sector (see table 1) highlights a growing integration of smart technologies such as the Internet of Things (IoT), Machine Learning (ML), and Deep Learning (DL) for asset monitoring and failure prediction. Lugarà (2018) emphasises the foundational role of IoT and real-time data streams in enabling condition-based monitoring and proactive maintenance strategies. A comprehensive survey of ML/DL applications in railway maintenance reveals a shift from reactive and scheduled interventions to data-driven predictive models, particularly for rolling stock, rail infrastructure, and switchgear components. Several studies explore different technological and operational focuses (Davari et al., 2021). For instance, in the U.S., wayside detectors are used to monitor axle temperatures, wheel wear, and vibrations, enabling targeted inspections and reducing unplanned downtime[3]. In contrast, a French case developed by Alter Solutions[4] integrates cloud-based 3D recognition and anomaly detection models to manage track and infrastructure maintenance. In Sweden, multibody simulations are applied to optimise wheel-rail interaction and anticipate wear on Iron-Ore lines, enhancing asset longevity and safety (H-Nia et al., 2023). Several studies explore different technological and operational focuses (Davari et al., 2021). For instance, in the U.S., wayside detectors are used to monitor axle temperatures, wheel wear, and vibrations, enabling targeted inspections and reducing unplanned downtime[5]. In contrast, a French case developed by Alter Solutions[6] integrates cloud-based 3D recognition and anomaly detection models to manage track and infrastructure maintenance. In Sweden, multibody simulations are applied to optimise wheel-rail

[3] The studio is promoted with IBM and features collaboration with Dhaivat Parikh, Qing He, Zhiguo Li, Buyue Qian, Dongping Fang, and Arun Hampapur.

[4] https://www.alter-solutions.com/case-study-railway-infrastructure-data?.

[5] The studio is promoted with IBM and features collaboration with Dhaivat Parikh, Qing He, Zhiguo Li, Buyue Qian, Dongping Fang, and Arun Hampapur.

[6] https://www.alter-solutions.com/case-study-railway-infrastructure-data?.

interaction and anticipate wear on Iron-Ore lines, enhancing asset longevity and safety (H-Nia et al., 2023).

Table 1: Summary of studies on Port 4.0 aspects.

Author(s)	*Business Model adopted*	*Key Variables*	*KPIs*	*Key Innovations*	*Main Outcomes*
Fahim et al. (2021)	Open data-sharing to promote transparency and collaboration	Data accessibility, interoperability	Transparency, decision-making speed	Blockchain, open APIs	Faster, informed decisions, improved stakeholder trust and cooperation
Rodrigue et al. (2022)	Environmentally integrated logistics model	Sustainability metrics, logistics integration	Reduced environmental impact, cargo flow efficiency	Digital Twins, AI for logistics	Lower emissions, optimized cargo routing
Henríquez et al. (2020,2022)	Transition to a 5G/Port 4.0 model focused on smart technology adoption	Emerging technologies (IoT, AI, robotics, data analytics)	Ship turnaround time, cargo throughput, resource utilization	Big data, AI for operational optimization	Strengthened supply chain position through reliability, speed, and customer satisfaction
Kringelum (2019)	Multi-sided model supporting diverse customer needs and partnerships	Port user diversity: logistics companies, industrial firms, technology partners	Growth in customer segments, retention rates	Digital platforms for customer interaction	Enhanced customer retention, expanded market through diversified offerings
Nitsenko (2017)	Business model emphasizing sustainability and value creation	Value generation processes: logistics services, environmental practices	Economic impact (revenue growth, value-added contributions)	Green logistics, renewable energy, circular economy	Alignment with SDGs, measurable contributions to economic growth and environmental protection
Musso et al. (2022)	Unified port management integrating logistics and infrastructure	Port traffic volume, cargo movement frequency	Resource utilization rate, turnaround time, handling efficiency	Smart port tech: IoT, AI, data analytics	Attraction of global logistics partners, enhanced investment potential
Córdova and Durán (2014)	Efficiency-focused community model for small and mid-sized ports	Resource optimization, cost-effective processes	Turnaround time, resource utilization, logistics efficiency	Platforms for knowledge sharing	Streamlined processes, resource optimization, increased service quality
de Langen et al. (2020)	Circular economy-driven port ecosystem model	CE activities: recycling, material recovery, sustainable manufacturing	Growth rate of CE companies, resource recovery rate	Symbiotic relationships within CE ecosystem	Reductions in waste and emissions, alignment with circular economy principles

Advanced approaches also leverage AI and digital platforms. Hitachi Rail, for example, has implemented a digital twin-based PM platform for Spain's high-speed network[7], using big data analytics to reduce maintenance costs and improve infrastructure reliability. From a computational standpoint, recent innovations include the use of transformer-based deep learning models to detect axle vibrations and the BOLT-RM algorithm, which applies online learning and domain adaptation to continuously refine wheel defect predictions (Risca et al., 2025).

These studies vary in terms of focus—vehicle vs. infrastructure, offline vs. real-time learning, component-specific vs. system-level monitoring—but all converge on the strategic role of PM in improving safety, efficiency, and sustainability. Notably, the integration of railway PM within port ecosystems remains underexplored, particularly in Southern Europe, where predictive approaches could significantly enhance rail-port interoperability and resilience.

Leading ports such as Rotterdam and Barcelona illustrate how dynamic capabilities can guide strategic innovation. Rotterdam integrates digital infrastructure and innovation labs to maintain leadership in global logistics (Casper van der Woude, 2021), while Barcelona promotes sustainability and stakeholder collaboration through integrated smart technologies (Henríquez et al., 2022). Nonetheless, research still lacks a comprehensive view of how digital ecosystems—especially those involving predictive maintenance—can support integrated and sustainable rail-port models. Tools such as the performance monitoring framework developed by Nitsenko et al. (2017) offer insights into innovation and resilience. Yet, further research is needed to understand how multidimensional innovations and complementary assets—such as blockchain, digital twins, and standardised data platforms—can strengthen logistics networks and enable circular economy practices.

This study adopts the As-Is/To-Be methodology to evaluate the integration of PM in rail-port logistics. Widely used in business process reengineering and digital transformation (Hammer and Champy, 2009; Tijan et al., 2021), this approach compares the current operational state with a future, optimized scenario. The As-Is scenario at the Port of Trieste highlights inefficiencies in manual maintenance practices, which increase costs and delay sustainability progress. In contrast, the To-Be scenario envisions enhanced operations through PM technologies, Digital Twins, and real-time monitoring, aligning with DCT to foster resilience, adaptability, and improved performance.

2.1 The case study

This section presents a description of the case study through two subsections: 1) technological implementation, 2) stakeholders' analysis and outcomes of the port process. Concerning the use case of this paper, the Port of Trieste (see Fig. 1) a key Mediterranean hub in the Trans-European Transport Network (TEN-T), is crucial for European and global trade, particularly in intermodal logistics[8].

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[7] https://www.hitachirail.com/case-studies/2024/spain-implementing-predictive-maintenance-with-advanced-technologies/?.

[8] www.adspmao.it

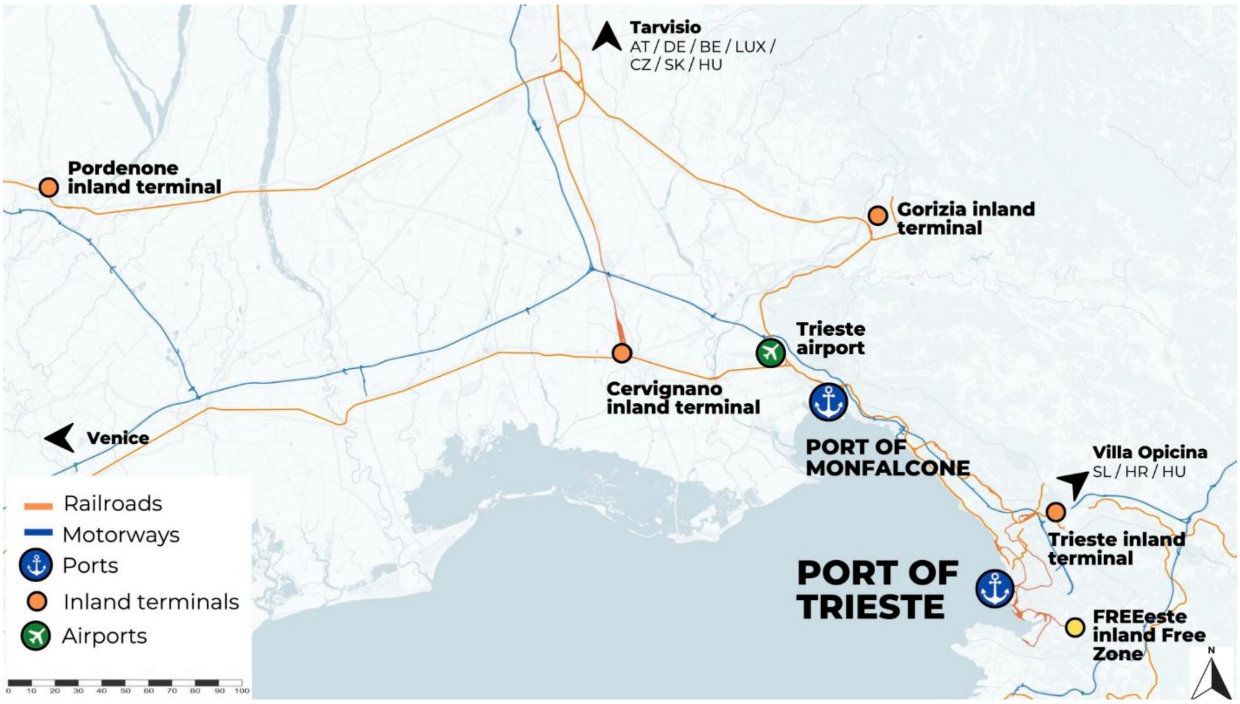

Figure 1: Map of the Port of Trieste, in Italy.
Source: NAPA (North Adriatic Ports Association).

The Port of Trieste is a strategic hub for sustainable rail freight, particularly in liquid bulk logistics via the Transalpine Pipeline. In 2023, it handled 55.6 million tons of cargo and 8,979 trains, with 54% of container traffic transported by rail—exceeding the EU's 2050 target of 50% modal shift (European Commission, 2023). As part of the AUTOSUP project, a Horizon Europe initiative, Trieste is being transformed into a fully automated and interconnected logistics platform. Digital Twins improve freight flow management, while blockchain ensures transparency and trust in logistics operations (Henríquez et al., 2022). Trieste's model generates measurable outcomes across three dimensions:

- Environmental: reduced CO_2 emissions and energy consumption per movement, supporting Green Deal goals (European Commission, 2023);
- Operational: predictive diagnostics reduce downtime and improve asset utilisation;
- Economic: higher logistics throughput and reduced maintenance costs contribute to financial resilience (Moya et al., 2023).

In comparison to leading ports like Rotterdam and Hamburg, where automation and real-time monitoring have cut downtime by up to 50% and improved resource allocation by 30% (Henríquez et al., 2022), Trieste shows similar benchmarks. Stakeholder collaboration under AUTOSUP—among port authorities, logistics operators, and local governments—has been essential. Blockchain and digital platforms support coordination and overcome barriers to PM adoption.

The introduction of new maritime corridors with North Africa further underscores Trieste's strategic role in Mediterranean freight flows and global trade integration (EU, 2023).

2.2 Predictive maintenance in freight railway systems

Predictive Maintenance represents a transformative shift in railway operations, moving from reactive to proactive strategies. Its primary aim is to monitor railcar and track conditions in real time, enabling early detection of issues to minimize breakdowns and downtime through a more complex process. Figure 2 illustrates the operational workflow that the Port of Trieste needs to implement within the AUTOSUP project for predictive maintenance in rail freight systems.

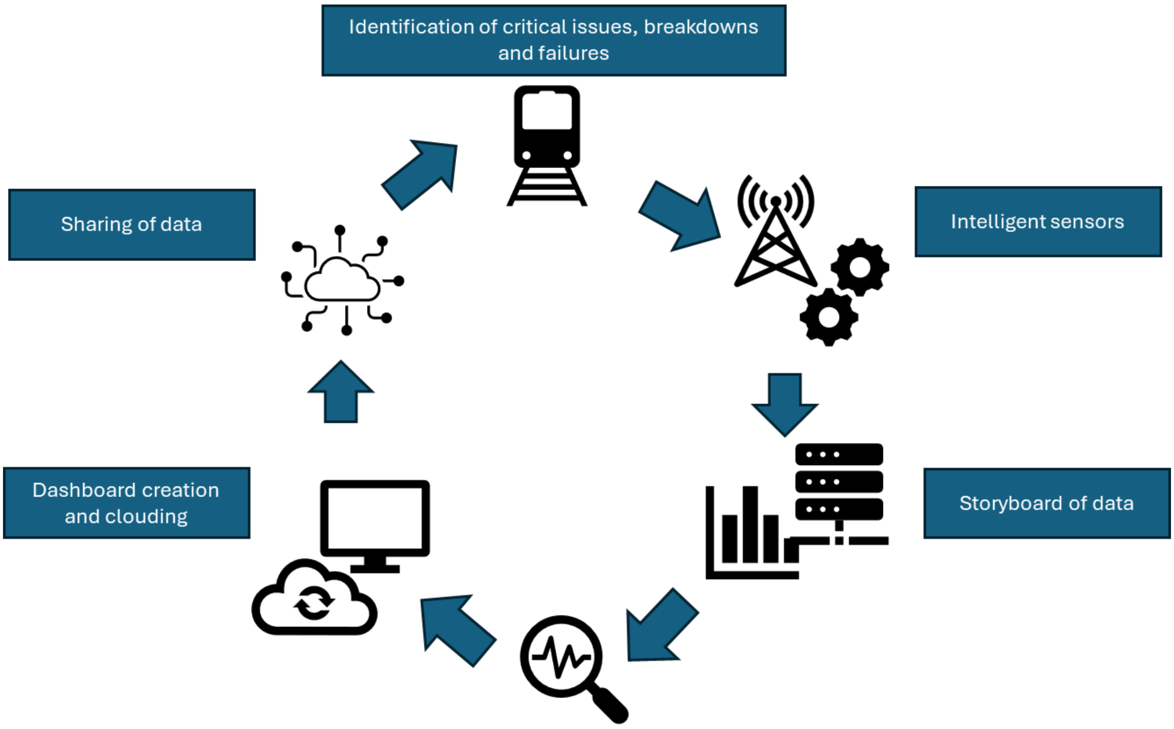

Figure 2: Automation 4.0 for the predictive maintenance.
Source: Elaboration of authors.

PM technique improves operational planning, extends asset lifespans, optimizes fleet use, and lowers delays and material waste—as seen in the Trieste case. This approach also reduces costs for logistics operators. Preventive strategies rely on pre-scheduled interventions based on fixed intervals (e.g. mileage, operating hours) to reduce the risk of unexpected failures. However, this model assumes predictable wear patterns and may overlook hidden or irregular faults, limiting its effectiveness.

Figure 3 illustrates the hierarchical structure of maintenance strategies, transitioning from corrective to predictive approaches.

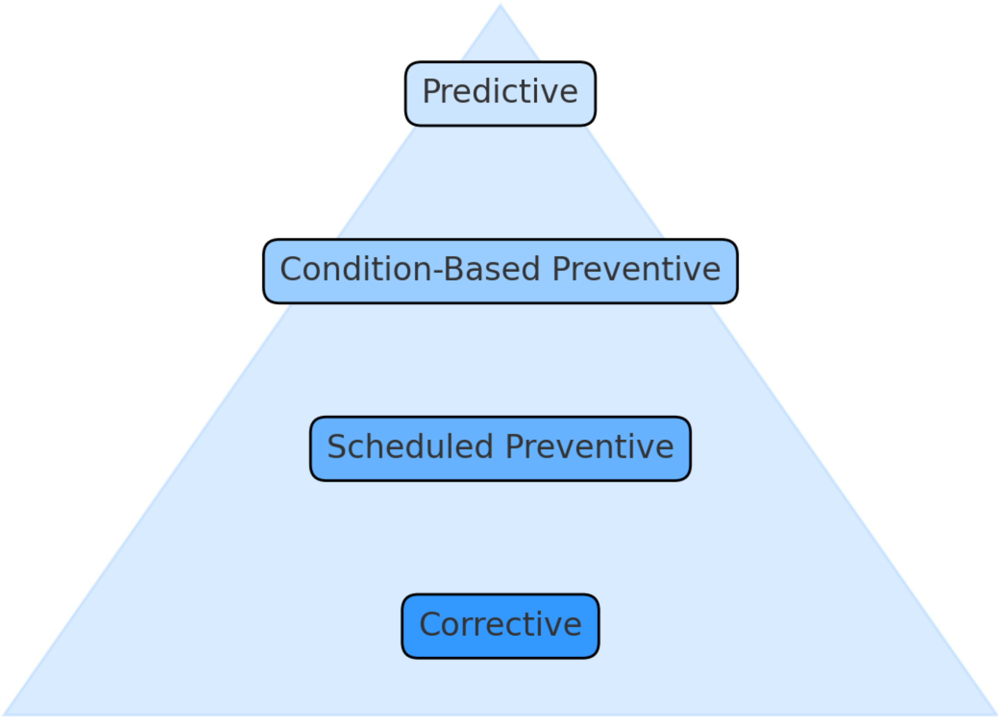

Figure 3: Levels of Maintenance: Preventive vs Predictive Maintenance diagram.
Source: Elaboration of authors.

To interpret this transition, the DCT (Teece et al., 1997) offers a strategic lens to understand how ports adapt to changing environments. DCT's foundational pillars—sensing, seizing, and transforming—are extended here with a fourth dimension: impact validation and benchmarking, crucial for monitoring digital transformation in rail logistics. This additional layer ensures regulatory alignment (e.g., TEN-T policies), assesses technology effectiveness and ROI, and supports benchmarking against leading European ports.

The model unfolds in four stages:

- Sensing: Identifies inefficiencies in traditional manual inspections and reactive maintenance. These gaps highlight the value of real-time monitoring through Predictive Maintenance.
- Seizing: Deploys IoT sensors, PM systems, and digital platforms that monitor wagon conditions, streamline shunting, and enhance resource use.
- Transforming: Shifts from outdated processes to a smart logistics model leveraging automation and data to improve reliability, capacity, and safety.
- Validating: Uses KPIs to measure results—reduced downtime, better service quality, and lower emissions—ensuring scalability and alignment with EU goals.

Evidence-based benchmarks reinforce this model. For instance, IoT monitoring in European freight corridors cut disruptions by 20–30% (Fahim et al., 2021); Hamburg's digitised cargo management improved rail productivity by 12%; ETCS automation in

Switzerland increased slot availability by 15%; and Antwerp-Bruges achieved a 14% gain in flow predictability. Predictive Maintenance alone has cut unplanned failures by 45% and maintenance costs by up to 20% (Moya et al., 2023).

3. Results and discussions

The Port of Trieste applies the DCT by leveraging *sensing* (e.g., IoT sensors for inefficiency detection), *seizing* (investment in renewable-powered systems and cold ironing), and *transforming* (data-driven processes and stakeholder engagement) to support adaptability, sustainability, and scalability in port ecosystems.

Innovation in freight railway operations at Trieste marks a shift toward proactive logistics, but broader adoption faces three key barriers: (1) limited capital in smaller ports and high infrastructure retrofitting costs, which can be mitigated through PPPs and pilot projects like AUTOSUP; (2) technical challenges, including legacy system incompatibility and fragmented implementation, addressable via phased upgrades as seen in Rotterdam; and (3) human factors, such as resistance to change and skills gaps, which require targeted training and stakeholder engagement to ensure alignment and workforce readiness.

As shown in Table 2, DCT enables competitive advantage through technologies that reduce downtime, optimize resource use, and align with EU climate targets. Benchmarking against ports like Rotterdam demonstrates pathways to replicability and competitiveness (Henríquez et al., 2022; de Langen et al., 2020).

To assess PM integration, KPIs were categorized into four dimensions: operational efficiency, financial performance, sustainability, and stakeholder collaboration. These KPIs were chosen for their relevance to EU sustainability goals and their ability to capture both immediate and long-term impacts of digital transformation:

1. Operational KPIs
2. Financial KPIs
3. Sustainability KPIs
4. Stakeholder Collaboration KPIs
5. Scalability and Competitiveness KPIs

Technological barriers—such as interoperability and cybersecurity—can be mitigated through standardized protocols and robust data-sharing systems (Rodrigue et al., 2022). Social concerns, including workforce displacement, call for capacity-building and stakeholder engagement (Fahim et al., 2021). Environmental impacts are addressed via energy-efficient technologies (Casper van der Woude, 2021), while regulatory complexity requires alignment with GDPR and international standards (Henríquez et al., 2022). Uncertain ROI can be mitigated through cost-benefit analyses that highlight long-term gains. Finally, strong industry collaboration, as in Rotterdam, supports system integration and scalability (de Langen et al., 2020). The case of Trieste demonstrates how advanced maintenance systems, integrated with IoT sensors and digital twins, can enhance efficiency, sustainability, and competitiveness in freight transport (Teece et al., 1997). These technologies enable data-driven diagnostics and real-time analytics, reducing delays, optimising resource use, and improving reliability (Ciocoiu et al., 2017). Similar advancements in ports like Rotterdam and Hamburg have improved intermodal flows and operational performance (Rodrigue et al., 2022), showing how PM contributes to the transition from reactive to proactive maintenance.

Table 2: Value creation in railway-port integration. Elaboration of authors.

Domain	*KPIs*	*Purpose*	*References*
Operational Efficiency	Average Inspection Time per Wagon (hour/wagon)	Measure efficiency in inspection times	Henríquez et al., 2022
	Unplanned Downtime (hours/month)	Track reduction in downtime	
	Wagon Availability Rate (%)	Indicate wagon operational readiness	
	Maintenance Cycle Time (days)	Evaluate time taken for maintenance	
Cost Efficiency	Maintenance Cost per Wagon (€)	Assess cost reductions in maintenance	de Langen et al., 2020; Henríquez et al., 2022;
	Logistics Throughput (TEUs/day or tons/day)	Measure goods handling capacity	
	Revenue per Rail Movement (€)	Track financial performance per rail movement	
Environmental Sustainability	CO2 Emissions per Freight Movement (kg/ton-km)	Monitor emission reductions	UN, 2015
	Energy Consumption per Train Movement (kWh)	Evaluate energy efficiency improvements	
	Material Waste Reduction (%)	Assess progress in material reuse/recycling	
Stakeholders' Collaboration	Communication Response Time (minutes)	Track resolution speed for coordination issues	Henríquez et al., 2022
	Stakeholder Satisfaction Index (score out of 10)	Gauge stakeholder satisfaction levels	
Scalability and Competitiveness	Number of Benchmarking Metrics Met (count)	Monitor alignment with best practices	de Langen et al., 2020; Rodrigue et al., 2022
	Adoption Rate of Digital Tools (%)	Measure adoption of digital tools	
	Intermodal Connectivity Score (scale of 1 -10)	Assess integration of rail and port logistics	

The paper addresses RQ1, examining how rail-sector innovation enhances logistical performance while advancing EU decarbonisation objectives (UN, 2015). Economically, Trieste's increased throughput and higher revenue per train demonstrate the financial benefits of automation and intermodal integration. Addressing RQ2, the port of Trieste port can serve as model for other ports across their smart port transformation (Henríquez et al., 2022).

Environmental indicators—such as lower emissions per train and reduced energy consumption—confirm the port's alignment with EU climate policy. Digital platforms, inspired by governance models in Hamburg and Barcelona, enhance transparency and cooperation across the logistics chain (Kringelum, 2019).

On a policy level, stronger integration within TEN-T corridors requires investments in IoT and digital twin infrastructure, improving freight optimisation and emissions tracking. Blockchain-enabled governance, as in Hamburg, enhances coordination and decision-making. Policies should also promote renewable-powered systems and interoperable platforms to reduce data silos and accelerate the green transition (Henríquez et al., 2022). These findings align earlier studies on digitalisation in Adriatic logistics

(Mazzarino et al., 2022a; Braidotti et al., 2020), which stress the importance of coordinated governance and hinterland connectivity for regional competitiveness.

This study addresses RQ1 by demonstrating how predictive maintenance reduces downtime, extends asset lifespans, and improves energy efficiency in rail-port systems. In response to RQ2, the paper shows how the Dynamic Capabilities framework guides the integration of digital tools, enhancing adaptability and stakeholder coordination. Overall, the Trieste case illustrates a replicable model where PM and DCT jointly drive sustainable and resilient logistics aligned with EU decarbonisation goals.

Finally, workforce development is crucial. Training on digital tools, predictive analytics, and AI ethics—as implemented in Rotterdam and Hamburg—prepares workers for smart port operations. Such programmes not only build digital capacity but also mitigate resistance to automation. Aligning innovation with regulatory and human strategies enables ports like Trieste to bridge the gap between ambition and implementation, becoming resilient nodes within global freight systems.

4. Conclusions

This study examines the transformation of the Port of Trieste into a smart port through Industry 4.0 technologies, using DCT as an interpretive lens. It contributes to the theoretical understanding of how ports can sense, seize, and reconfigure resources to foster efficiency, sustainability, and resilience in rail-port integration. Practically, it shows how innovations such as PM reduce downtime, extend asset lifespans, and align operations with EU decarbonisation goals, positioning Trieste as a replicable model within the TEN-T network. However, the research highlights critical barriers, including financial constraints, skill shortages, and infrastructural rigidity, which limit the scalability and seamless adoption of digital solutions. Addressing these limitations requires targeted investments, capacity-building, and governance innovation. Future research should explore the long-term impacts of smart technologies, ethical AI integration, human–machine collaboration, and comparative benchmarking with other ports. Cross-sectoral insights and policy frameworks that support institutional coordination and stakeholder engagement are also essential. Overall, this study advances both theoretical and operational knowledge on sustainable digital transformation in port logistics.

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