Port-System-Innovation: A Comprehensive Model for Freight Railway Digital Automation. A Case Study of Trieste Port, Italy

Irina Di Ruocco[1(✉)] and Marco Mazzarino[2]

[1] Department of Economics, Mathematics and Statistics, University of Trieste, Via Alfonso Valerio, 4/1, 34127 Trieste, Italy
irina.diruocco@deams.units.it

[2] Department of Architecture and Arts, Università IUAV of Venice, Ca' Tron, Santa Croce 1957, 30135 Venice, Italy
mazzarin@iuav.it

Abstract. The integration of new freight transport technologies into port areas requires a detailed understanding of success factors, drivers, and barriers — with the Port of Trieste serving as a representative territorial case. In this context, the local rail operator plans to implement predictive maintenance solutions for freight transport. Although several research gaps remain, this study aims to explore how technology is embedded within the territorial context, assessing the opportunities and vulnerabilities of port–territory synergies from an innovation-driven perspective.The article proposes a holistic model that incorporates territorial, technological, geographic, and port-related dimensions to analyse the integration of predictive maintenance through a geographic-economic lens. The model supports the case study and provides insights for replication in other port environments.

Keywords: railway automation · port-city integration · predictive maintenance

1 Introduction

The perception of port systems is evolving beyond being merely a logistical infrastructure to that of an innovation ecosystem— an inherently geographic system which brings together technology, governance and stakeholder cooperation to address environmental, economic and spatial issues [1, 2]. Ports play an important role in the global trade system [3] but high utilisation of maritime and logistic activities produce numerous layers of environmental pressure, from air and water pollution to ecosystem degradation [4], alongside urban pressures faced by adjacent communities [5]. Recent technological advances, both digital technologies used in port areas [6] and data-based methods, have changed the ability to monitor, assess and mitigate overall, manage environmental pressures, across a port territory [7]. New tools, such as PM for freight trains operating in the port sector, contribute to a better understanding of port impacts- both marine and land-based- facilitating the use of digitally enabled planning applications in alignment with objectives of sustainable urban and regional development [8].

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2026
O. Gervasi et al. (Eds.): ICCSA 2025 Workshops, LNCS 15894, pp. 125–141, 2026.
https://doi.org/10.1007/978-3-031-97648-3_9

In addition, port system issues involve stakeholder groups— public authorities, private operators, logistics companies and communities—with whom relationships influence the whole supply chain's operational performance and resilience. According to [9], port management is now reliant on whatever funding, digital convergence and decision-making formats are developed to respond to sustainability implications and user expectations. Within this context, planning sustainable port logistics can no longer be seen as only infrastructure provision, but also the design of governance models that optimise for innovation [10].

Still, barriers such as aging infrastructure, fragmented policy frameworks, and limited technology integration still inhibit the development of coherent, resilient port systems across Europe. In order to attain the European Commission's modal shift objectives (2021, 2023) [11, 12] (for example, an increase of rail freight share to 30% by 2030), the sector must invest in technologies such as predictive maintenance [13], the Internet of Things (IoT) and Digital Twins (DTs), but also embed these technologies and tools into a broader territorial innovation strategy.

This paper provides a case study of the port of Trieste; a context, in which innovation on the territory (like predictive maintenance) not only includes an innovation in technology but also geographic-territorial innovation and an economic innovation can develop a synergy between port and territory while advocating a vision of innovation ecosystems in the case of digital technology, like predictive maintenance in rail freight context, focused on collaboration between ports, businesses, public authority, and communities. In these ecosystems, the smart port technology acts as spatial drivers of transformation. The smart port technologies contribute to the regeneration of port-adjacent areas, enhance regional connectivity, and support inclusive and sustainable urban development [14].

This study is guided by two key research questions:

1. How can technological innovations in railway and port systems support urban and territorial policies aimed at sustainability of port-adjacent areas?
2. In what ways can the integrated planning of freight flows and logistics automation contribute to the spatial and functional transformation of territories, fostering better alignment between transport infrastructure and regional development?

The Port of Trieste offers a compelling case study in this regard. As Italy's leading rail-connected port, it operates as a gateway to Central and Eastern Europe yet faces structural and technological challenges that limit its capacity for transformation. The AUTOSUP (Autonomous of Supply Chain), a Horizon European project [15] addresses these issues by promoting digital railway automation, port-hinterland integration, and circular logistics planning—demonstrating how targeted innovation policies can reinforce the role of ports as active agents of sustainable territorial development.

The structure of the paper is as follows. Beyond this introduction, Sect. 2 describes the literature review. Section 3 presents the research methodology, the results and discussion are presented in the Sect. 4. Finally, the Sect. 5 draws the conclusions.

2 Literature Background

Recent research on the innovation of port areas, moving towards the idea of "Smart Ports or Ports 4.0," increasingly highlight the need to think of port areas as complex urban and regional systems [16], where infrastructure, economic activity and environment coexist, and even overlap, in a situational context [17]. With growing global trade and expanding cities, port territories are increasingly prompted to handle this complexity, whilst pursuing sustainable development and technological innovation [18]. In this context the innovation ecosystem of ports and cities concept has emerged – ports not as merely logistical gateways, but as places for knowledge generation, inter-organisational learning, and social-economic reformation [19]. Port authorities can fulfil an increasingly important role of platform organiser in these ecosystems, which include not only holding and maintaining infrastructure, but also mediating multi-level cooperation, digital transformation, and sustainability transition. This role is increasingly crucial in dry ports and hinterland terminals, where rail infrastructure collectively with land use and environmental imperatives is increasingly prevalent, urging integrative planning and circular economy.

Although there is increased research on smart ports, there are still significant research gaps, especially regarding the rail-port interface. Research has primarily investigated maritime automation, urban regeneration, or as straying distinct technological tools, while we do not yet fully understand how technologies including the emerging PM, digital twins' technology (DTs), and real-time analytics—are integrated into governance systems, territorial planning [13], and policy engagement in port-hinterland systems [20, 21]. Although the Smart Port 4.0 paradigm has opened potentially disruptive technologies—Internet of Things (IoT), big data, blockchain, PM—into logistics, research has not fully studied how these tools affect the durability of the infrastructure, the reductions in emissions or resilience in planning for port-rail Networks [22, 23]. Predictive maintenance is an emerging area that could help in many ways, including less downtime of operations, longer asset life cycles, or less emissions. Although we can broadly categorize these as emerging technologies, there is rarely anything that analyses how PM is governed at different institutional levels or how PM is used in the governance of spatial development [24]. Additionally, there are currently monitoring frameworks that typically measure a limited number of operational metrics and do not capture a multi-scalar, cross-sectoral understanding of port-city-hinterland innovations [25]. Research has rarely considered the proximity dimensions—as territorial, cognitive, organisational, institutional—and how they shape outcomes of innovation or the design of processes for collaborative governance arrangements [26].

This research study seeks to address these gaps by providing a territorially grounded analytical model to understand how freight digitalisation as predictive maintenance is transforming both operations and governance in the rail-port context. Authors focus on the Port of Trieste as a strategic access point in Southern Europe to ascertain how these changes are being diffused into the institutional landscape of ports using circular economy principles and urban-regional policy positions. The novel contribution is

based on our approach that draws on economic and transport geography, and institutional theory to construct the Spatial-Institutional Innovation Model (SIIM)—a multidimensional framework that tells the story of not only spatial embeddedness, governance arrangements, innovation ecosystems, and sustainability pathways.

Ultimately, this study contributes to the literature by demonstrating how the port-city-hinterland interface can become a space of co-created value, where digital innovation, multi-actor governance, and territorial proximity converge to support resilient and sustainable transformation.

3 Materials and Methods

3.1 The Case Study

This part details the case study of the Port of Trieste as a strategic and technological hub in the Mediterranean and the Trans-European Transport Network (TEN-T) with emphasis on sustainability, innovation, and intermodal freight logistics. Trieste is strategically located at the crossroads of Southern and Central Europe, acting as a critical gateway, linking maritime routes to inland logistics corridors through automation and PM (Fig. 1).



Fig. 1. Location of Trieste Port. Elaboration of authors on source www.yacht.de

The geographic and strategic advantages of Trieste strengthen its role as a key intermodal logistics centre in the Mediterranean and the broader TEN-T. The port of Trieste handled 59,540,505 tons of merchandise, reflecting a 7.1% increase on the previous year that was driven by the increase of 10.6% of liquid bulk cargo measured at 41,261,754 tons. An increase of 1.8% in general cargo rose to 18,157,699 tons, and container activity generated 841,867 TEUs (-1.2%) – consisting of 608,327 full (4.0%) and 233,540 empty containers (-12.6%) – and with ro-ro activity that recorded the transit of 295,386 vehicles (-1.1%). Dry cargo declined by -72.7% to 121,052 tons, a decline – clarified the Shipping

Specialist of the Port System of the Eastern Adriatic Sea – which is attributable to the absence of activity in metallurgical products during the year, while cereals increased by 13.0% to 75,331 tons [27, 28]. Rail activity to and from the terminal was 11,147, with a decline of −9.9% attributable to the improvement of the networks (Austria, Germany, Czech Republic, Slovenia) and the inclement weather conditions throughout Central Europe that had a significant impact on overall rail activity.

The rail freight operations in the Trieste-Monfalcone corridor demonstrate the port's commitment to modal shift and decarbonisation targets, aligned with European environmental targets [22]. The underlying philosophy of the Trieste revitalisation is about technological innovation and digital logistics. One important initiative is the AUTOSUP project (Automated and Safe Multimodal Freight Transport), which receives co-funding under European programmes [15]. The AUTOSUP project intends to implement predictive diagnostics, digital twins, and real-time tracking, with the aim of transforming Trieste into an intelligent and automated freight hub, developing intermodal integration further, and ensuring the role of the Mediterranean in a more circular and sustainable logistics system (Fig. 2).

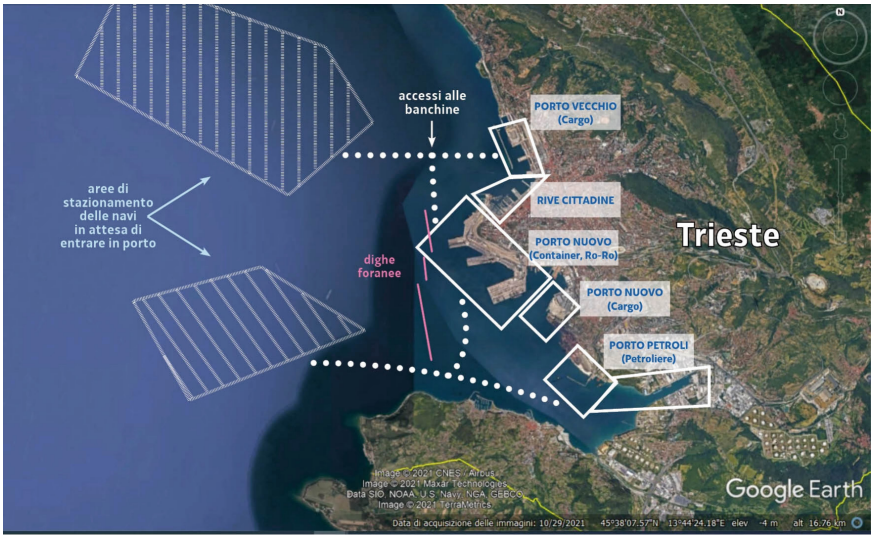

Fig. 2. Functional areas in the port of Trieste. Source: ARPA FVG.

A distinctive feature of AUTOSUP is its alignment with the Physical Internet (PI) paradigm. The Physical Internet is an emerging logistics model inspired by the data-based Internet. It envisions a hyperconnected, open, and modular system for freight transport, where goods are packaged in standardized, reusable containers—referred to as "π-containers" [29] and dynamically routed through shared, interconnected logistics networks using digital platforms, real-time data, and predictive analytics [30].

Through AUTOSUP, by utilising the PI, Trieste not only improves the efficiency and responsiveness of its freight system but also catalyses systemic change in European logistics—toward standardisation, decarbonisation, and interoperability across borders.

This support for the systemic change underscores Trieste's role as a model port in the use of Smart Port 4.0-style strategies, and to the EU's long-term vision of sustainable transport. As we have underscored, sustainability is built into the operating model for the Port of Trieste, which has pursued advanced technologies and circular economy principles towards efficiency and positive environmental performance. Building on that work and approach, Trieste now has a circular economy model tailored to the rail sector. The port systematically employs maintenance, reuse, and recycling practices via refurbishment programmes, whereby worn-out parts are either replaced or repurposed. This supports a lower demand for virgin raw material and helps to lower the port's overall environmental impacts. The application of lightweight components and fuel-efficient technologies also assist the performance of wagon fuel and these both can drive significant reduced CO_2 emissions.

Central to these achievements is a strong culture of stakeholder collaboration. Through the AUTOSUP project [15], Trieste is facilitating the technical standardization and regulatory harmonization necessary to support cross-border multimodal transport.

Beyond operational excellence, the geographical framework of Trieste is emerging as a true innovation leader within the port community. This holistic approach provides a replicable and scalable framework for other ports aiming to enhance rail integration, decarbonise logistics chains, and meet the EU's sustainability objectives. In both performance and governance, Trieste illustrates the transformative potential of forward-thinking port ecosystems in shaping the future of European freight transport [31].

3.2 Methodology: The SIIM Model

This research proposes and applies a place-based model of analysis for economic geography that investigates how local governance, institutional configurations and spatiality shape innovation in sea-logistics - specifically digitalisation and automation in port-rail systems. The Port of Trieste is the single case study and serves a useful context to explore and demonstrate the explanatory capacity of the model. The method is designed around the establishment of a Spatial-Institutional Innovation Model (SIIM) specifically tailored to analyse transport innovation in economic geography taking into account [32], which involves, 1) the spatial logic of transport geography; 2) the spatial logic; 3) the Institutional logic [33, 34]; and 4) the Sustainability reference [11, 12]. The model proposed here offers several strategies for researchers and practitioners within the governance-oriented lens of institutional analysis to develop a hybrid model to capture the multi-dimensionality of innovation in logistics hubs.

The model is structured along four key analytical dimensions "TIIC", as previously described, as shown in Fig. 3:

1. Territorial Embeddedness: this dimension analyses the strategic position of Trieste within the Mediterranean and TEN-T corridors, with attention to rail-port integration, hinterland access, and connectivity to Central Europe [11].
2. Institutional Architecture: drawing from the Institutional Analysis and Development (IAD) framework [33], this section investigates how local, national, and European governance structures interact to facilitate or constrain digital innovation. The AUTOSUP project is examined as a regulatory and institutional experiment, highlighting

the coordination between port authorities [35], logistics operators, and EU policy instruments [11, 14, 18].

3. Innovation Ecosystem: this part evaluates how Trieste functions as a logistics innovation hub [36, 37], analysing the port's engagement with EU-funded projects, its adoption of digital twins, real-time monitoring, and the use of predictive diagnostics in collaboration with public and private stakeholders.
4. Circularity and Sustainability: the final dimension assesses how sustainability is embedded in port operations through a circular economy approach to rail assets, including maintenance, reuse, and material optimisation. In particular, the implementation of predictive maintenance technologies, based on IoT sensors, AI analytics, and digital twins, allows for condition-based interventions that reduce resource consumption, material waste, and CO_2 emissions—enhancing both efficiency and environmental performance [4, 22].

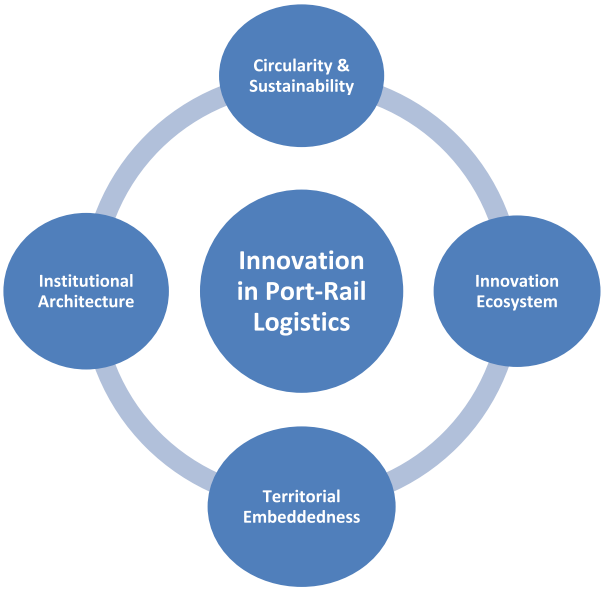

Fig. 3. Spatial-Institutional Innovation Model (SIIM) – Applied to Port of Trieste. Elaboration of authors.

Figure 3 depicts the port-territory integration in terms of innovation through the adoption of predictive maintenance for trains. The core block (Core Focus) is innovation in port-railway logistics (case study of Trieste) with the aim of implementing a more efficient model from the perspectives of governance, institutional context and spatial dynamics. At the same time, it requires attention to the new port reform that will be implemented shortly and that we will consider in the project Autosup. Surrounding it, we find the four pillar dimensions (TIIC) – represented in the immediate periphery of the core. Dimension No. 1) Spatial incorporation: it includes the location of the port of Trieste in the TEN-T and Mediterranean corridors and exploring the potential of the railway

undertaking for predictive maintenance. It is worth reiterating that the goal is not solely to carry out predictive maintenance, but this action presents an opportunity to move forward on the Rail-Port Integration improving connectivity to Central Europe and increasing its strategic function in regional networks. Dimension 2. Institutional Architecture builds on Ostrom's [34] IAD framework for multi-level governance (local–EU). It provides a visual representation of the railway undertaking's role in the AUTOSUP project. This role acts as a coordinating platform, ensuring permanent alignment between policy, regulation, experimentation, and decision-making. Dimension 3) Innovation Ecosystem relates to Europe's managerial and financial challenges. It aims to create decision-support tools to finance the use of digital twins for real-time monitoring. It also seeks to increase public-private collaboration and to enable predictive diagnostics and data-driven decision making. Finally, dimension aspect 4) Circularity and Sustainability gives the ability to align innovation, land and some environment. PM and condition-based maintenance through IoT and AI supports reuse and optimisation of railway assets such as freight wagons, to reduce CO_2 emissions waste and resource usage and improve environmental performance.PM within the port of Trieste is explored through this prism as a single case study and is examined using both primary and secondary evidence, including institutional reports, project documentation (AUTOSUP), EU policy frameworks, and interviews with key authors undertaking during the opening phases of a project. Using this model when studying Trieste produced a technique for a replicated analysis of innovation within other port systems and added to a theoretical advancement of economic geography that is applied to transport and logistics.

4 Results and Discussions

Using the SIIM in the Port of Trieste shows the nature of transformation as a multi-dimensional event influenced by the territorial context, institutional configurations, technological innovations, and operating under the conditions of a circular economy, within the 4 dimensions – TIIC. The findings demonstrate how digitalisation – especially through predictive maintenance, real-time diagnostics – is affecting the operation itself as well as the governance in this strategic European logistics destination. The study findings are organised in Tables 1, 2 and 3, layered across three systems; indicating the connections between mutual territorial vulnerabilities, pertaining to the state of art in the territorial context; the logic for innovation; and systemic impacts, resting again within SIIM dimensions. Finally, Table 3 presents the systemic impacts.

The three tables representing the model proposed in this study are described in detail in the sub-sections that follow. Territorial Embeddedness: Trieste's singular geographic location along the Baltic-Adriatic TEN-T corridor, along with a strong rail connection to Central Europe, ensures the port is an important intermodal node. The incorporation of rail freight terminals, including the Trieste-Monfalcone location, additionally deepens the port's hinterland embeddedness. Overall, this spatial context supports the efficient movement of goods across the Alpine region, reduces congestion on the roadway, and contributes to European sustainability objectives. The results align with previous research on the relationship between spatial proximity [37] to industrial environments and the infrastructure planning process, as key features that framed the port's innovation

Table 1. Layer 1: Territorial Vulnerabilities (Drivers for Innovation). Elaboration of authors.

Dimension	Description	Innovation Need	References
Infrastructural Fragility	Ageing rail infrastructure, bottlenecks, low interoperability	Predictive maintenance, system monitoring	[12, 22]
Institutional Fragmentation	Overlapping competencies, regulatory misalignment	Blockchain governance, multi-actor coordination	[33]
Geographic Peripherality	Peripheral position in EU logistics, lower investment attractiveness	Strategic repositioning via rail corridor integration	[32]
Environmental Stress	Emissions, land use conflicts, lack of sustainability in planning	Circular economy, energy-efficient systems, environmental KPIs	[11, 34]

Table 2. Layer 2: Innovation Mechanisms (SIIM Dimensions). Elaboration of authors.

SIIM Dimension	Role in Addressing Vulnerabilities	Key Tools and Practices	References
Territorial Embeddedness	Enhances intermodal and hinterland connectivity, improves spatial integration	TEN-T rail integration, freight terminal optimisation	[2, 11, 32]
Institutional Architecture	Facilitates multi-level policy alignment, enables experimentation	AUTOSUP project, digital governance platforms, EU funding schemes	[22, 33]
Innovation Ecosystem	Creates a collaborative environment for technology adoption and adaptive learning	Predictive diagnostics, digital twins, partnerships with academia/industry	[1, 35]
Circularity & Sustainability	Embeds resource efficiency and environmental responsibility into infrastructure strategy	Circular asset management, energy-efficient materials, CO_2 reduction targets	[4, 11, 21]

pathway [38]. Institutional Architecture: Trieste's digital transition is enabled through a multi-level governance mechanism, whereby the Port Network Authority, regional government and EU institutions create an interconnected policy framework. The AUTOSUP project showcases how regulatory alignment and collaboration between stakeholders can expedite the adoption of advanced logistics enabled technologies. Innovation Ecosystem: the port of Trieste has evolved into a regional innovation ecosystem, leveraging new and established technologies. In addition to port infrastructure, technologies are being used

Table 3. Layer 3: Systemic Impacts (Outcomes for Ports and Territories). Elaboration of authors.

Impact Domain	Description	Long-Term Effects	References
Operational Resilience	Increased reliability and foresight of logistics systems	Reduced failures, adaptive infrastructure	[21]
Territorial Attractiveness	Improved competitiveness and capacity to attract innovation and investment	Repositioning in EU logistics, private sector engagement	[2, 38]
Regional-Hinterland Integration	Stronger spatial and functional links between port, city, and hinterland	Smoother modal integration, regional value creation	[35]
Sustainability Performance	Reduction of emissions, optimisation of resource use, better land stewardship	Contribution to European Green Deal targets	[4, 12, 21]
Innovation System Maturity	Institutional and cognitive capacity to innovate collaboratively	Knowledge transfer, learning platforms, replicability of solutions	[25, 39]

on rolling stock so operators can predict failures, lifecycles and down time. The results also show that while these technologies are more advanced at the operational level, their use in urban planning and regional development is lacking. Circularity and Sustainability: the investment in predictive maintenance has already produced results: maintenance costs have been reduced up to 30% and delays have been reduced in Spanish ports [16, 17]. Moreover, the European port in question has moved towards a circular economy for rail assets, with refurbishment and reuse of wagon components, reducing the requirement for raw materials, and extending the lifecycle of assets. Nonetheless, gaps remain in the full integration of digital sustainability practices into strategic planning. While the technologies are present, their use for environmental performance monitoring, energy optimisation, and carbon footprint reduction is still underexploited. Cross-Dimensional Insights: the case of Trieste underscores the interdependence between territorial proximity, institutional capacity, and technological innovation. The results confirm that predictive maintenance is not just a technical function but a governance and planning tool that can drive broader sustainability and resilience objectives—if embedded within coherent spatial and regulatory strategies.

4.1 Territorial Vulnerabilities and the Role of Innovation

The application of the SIIM model to the Port of Trieste also highlights a set of territorial vulnerabilities that digital innovation helps to address. These vulnerabilities emerge across multiple key factors as drivers/barriers [39]: 1) infrastructure fragility, 2) institutional fragmentation, 3) geographic peripherality, and 4) environmental stress, that are exposed as follows.

Infrastructural Vulnerability: Trieste's ageing rail infrastructure and the complexity of managing cross-border freight flows through the Alpine region expose the port to logistical bottlenecks and inefficiencies. Predictive maintenance directly addresses this vulnerability by anticipating failures, reducing downtime, and extending the lifecycle of critical assets. The shift from reactive to predictive models is especially valuable in contexts with limited redundancy and high throughput, ensuring resilience under strain [24].

Institutional Vulnerability: the fragmented governance landscape—characterised by overlapping competencies between regional, national, and EU institutions—creates risks of regulatory misalignment. Through the AUTOSUP project, Trieste has experimented with multi-actor digital governance, facilitating interoperability and reducing transaction costs in freight coordination [40].

Spatial and Economic Vulnerability: as a peripheral port in the European logistics hierarchy, Trieste faces challenges in competing with Northern Range ports and attracting long-term investments, and with the Spanish Barcelona port, running into smart posts [16, 17]. However, its strategic integration into the TEN-T Baltic-Adriatic Corridor and the deployment of smart technologies repositions the port as a value-added innovation hub, improving its connectivity and enhancing its economic resilience. By strengthening its role as a rail-integrated gateway, Trieste reduces its dependence on road transport and mitigates carbon-intensive vulnerabilities.

Environmental Vulnerability: port practices are often deployed in places that are more environmentally sensitive due to emissions, noise or land use issues. Predictive maintenance, energy-efficient rolling stock and circular asset management are approaches for improving the environment footprint of port logistics. Perspectives and Implications of SIIM Model: by acknowledging vulnerabilities, this study reaffirms the premise that technological innovations must be place-sensitive. In the case of Trieste, the digital transition is, in addition to a performance driver, a means of coping with territorial asymmetries, limits of infrastructure, and institutional complexity which reinforces the need for territorial specificity in innovation planning and development of technologies straited on the structural conditions of port systems. Moreover, it calls for innovation policies that are not just technology-driven, but informed by geographic-economic analysis, with the explicit goal of enhancing territorial resilience, functional equity, and sustainability in complex logistics ecosystems.

To represent the model and the vulnerability of the case study, the Fig. 4 describes the 3 levels of integration between port and territory through the innovation.

At the centre of the diagram are the key geographical vulnerabilities that generate limitations for the port-logistics system. These comprise the vulnerabilities of infrastructure (for instance, the ageing railway system is fragile and there is limited interoperability) and the vulnerable institutional environment resulting from governance fragmentation and misalignments in regulations. Vulnerabilities of geographical peripherality, meaning that the port plays a secondary role in comparison with the Northern Range ports, and environmental vulnerabilities, like emissions and land use pressures and impacts at a localised level, also constrain the opportunities for optimal development. The intermediate ring "applied solutions" illustrates the technological and organisational innovations

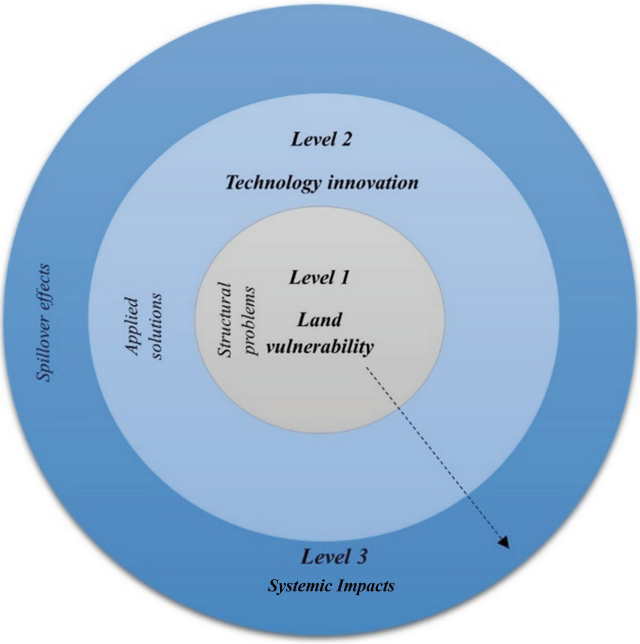

Fig. 4. Comprehensive Innovation-Resilience SIIM for the Port of Trieste. Elaboration of authors.

adopted to address these weaknesses. Predictive maintenance plays a central role in optimising asset performance and reducing system failures.

The outermost ring captures the systemic impacts generated by this innovation process, both for the port and the broader business ecosystem. Among these are improvements in operational resilience, with increased reliability and foresight in logistics operations. Trieste's growing economic attractiveness is reflected in its enhanced competitiveness and its ability to draw new investment. Territorial integration is promoted through better physical and functional linkages between the port, the city, and the hinterland. The model also reveals gains in sustainability and resource efficiency, with reductions in emissions and material consumption. Finally, the maturity of the innovation ecosystem is strengthened, positioning Trieste as a strategic node within the wider network of European smart ports.

4.2 Discussion and Further Implications

This research validates the notion that the Port of Trieste serves as an example of how innovation, especially predictive maintenance, digitalisation, and automation, can alter the relationships between infrastructure, governance, and territory. The authors use the SIIM to demonstrate technological and organisational transformation is addressing spatial and institutional vulnerabilities. The SIIM framework shows that, as demonstrated by Notteboom and Rodrigue [33], the analysis of Territorial Embeddedness can bolster the port's ability to support regional integration. The Institutional Architecture dimension of

the SIIM framework corresponding to Ostrom's [34] Institutional Analysis and Development (IAD) framework and Multi-level Governance (MLG) theory, as well as literature review on innovation ecosystems [39] emphasising institutional proximity for learning and collaboration, suggests the port authority's evolving role as ecosystem orchestrator [40] is especially relevant in hinterland logistics and land-use planning. The Innovation Ecosystem explains that new technologies such as predictive maintenance are embedded within local contexts which supports not just efficiency but specifically knowledge-based transformation. Cognitive and organisational proximity [37] acts as facilitators of co-innovation, trust, and adjustment of global solutions to local needs. However, embedding them into a wider plan is still underdeveloped, reinforcing [35], where smart port initiatives are noted to remain within silos [41]. Thirdly, the Circularity and Sustainability in Trieste aims to support the implementation of circular asset management—refurbishment, lightweight materials, and emission reductions—while reaching European goals [11]. However, the sustainability indicators are still not fully integrated into the innovation strategy. Predictive maintenance systems are even underutilised in terms of energy use and lifecycle metrics, thereby undermining the ability to create transformative change. A key contribution of this research is to recast innovation away from merely a growth agenda to one of responding to territorial vulnerability. The SIIM model suggests a resilience-based approach, where adaptation of spatial, institutional, and infrastructure vulnerabilities are featured distinctly. In Trieste, digital governance and predictive maintenance can not only benefit performance, but also reduce risk elements of system failure, gaps in coordination, and disadvantaged seated peripheries.

The concentric model developed in this research visualises how technological innovation interacts with deeper territorial dynamics. It offers a transferable tool for identifying vulnerabilities, aligning innovation with planning, and assessing systemic impacts across other port cities—particularly in contexts facing similar challenges of fragmentation, peripherality, and sustainability pressure (Table 4).

Table 4. SIIM application in Trieste's port: summary Matrix. Elaboration of authors.

Challenge	Innovation Response	Observed/Expected Result
Rail congestion and asset ageing	Predictive maintenance + digital twins	Reduced downtime, extended asset life
Regulatory fragmentation	Blockchain + digital governance platforms	Increased transparency, lower coordination costs
Economic peripherality	TEN-T integration + innovation branding	Enhanced logistics role, investment attraction
Environmental pressure	Circular economy practices + low-carbon tech	Lower emissions, better resource stewardship

Table 4 summarize the proposed framework emphasising how the importance of proximity-based collaboration, as outlined by [37] is fundamental also to run PM and DTs.

Port authorities are evolving from infrastructure managers to ecosystem orchestrators, improving the value-creation in port areas [42], facilitating digital transformation, sustainability transitions, and alignment with planning and regulatory frameworks (UN, 2015). There is a need to broaden evaluation metrics beyond throughput, incorporating indicators of resilience, urban integration, and sustainability, in line with [4, 11, 12, 22].

The framework serves for further research in different strategies, according to the findings of [43] on technologies for railway network:

1. Diagnostic – Identifies vulnerabilities like spatial marginality and institutional misalignment.
2. Strategic – Guides the use of predictive maintenance and governance technologies.
3. Evaluative – Supports assessment of short-term outcomes and long-term territorial impacts.
4. Replicable – Applicable to other port systems, especially in peripheral or fragmented governance contexts.

This research adds to the literature on territorial innovations by meshing ideas from economic geography, transport, and planning (23, 26, 38) and provides a multi-level perspective on how digital technologies are transforming logistics, governance, and spatial relations. The RQ1 on the role of innovation in terms of technology supporting urban and territorial sustainability is explored based on predictive maintenance, digital twins, and circular asset management. These concepts can be linked to emissions reduction, energy efficiency, and prolonging the useful life of the asset within environmental goals and urban strategies. The RQ2 on the territorial implications of integrated freight and automation is further evidenced based on the case of Trieste. Coordination of transport in the public and private sectors undertaken within the Baltic-Adriatic corridor in the TEN-T better connects regional territory elements, enhancing cohesion through integrated freight transport. Examples such as AUTOSUP synergize rail behaviour and automated transport to reshape port-city-regional relations through partnership, multilevel governance.

5 Conclusions

This article on the port of Trieste is part of the innovation of predictive maintenance, PM. Starting from this technology being tested for the port of Trieste by the railway company, the aim is to analyse the process of the port as an economic-geographical-territorial context, as well as to provide indications on the analysis of potentialities and vulnerabilities for the implementation of technologies. Taking a cue from the AUTOSUP project, this study offers decision support and researchers on a different key that unifies different sectors [8]. The limitations are related to the early stage of this study in the design phase, and to the collection of indicators, which is only qualitative in this step of research. Authors aim to offer a development with quantitative indicators in the next steps.

Acknowledgments. Authors thank the partner Adriafer S.r.l. for the technical support of the AUTOSUP project.

CRediT Authorship Contribution Statement: Irina Di Ruocco (Sects. 1, 2, 3.2, 4): Writing – review & editing, Writing – original draft, Supervision, Resources, Methodology, Investigation, Formal analysis, Conceptualization. **Marco Mazzarino** (Sect. 1, 3.1, 4.2, 5): Writing, Visualisation, Supervision, Conceptualization, Resources.

Disclosure of Interests. n.t.d.

References

1. Braidotti, L., Mazzarino, M., Cociancich, M., Bucci, V.: On the automation of ports and logistics chains in the Adriatic region. In: Gervasi, O., et al. Computational Science and Its Applications – ICCSA 2020. ICCSA 2020. Lecture Notes in Computer Science, vol. 12255, pp. 96–111. Springer, Cham (2020). https://doi.org/10.1007/978-3-030-58820-5_8
2. Di Ruocco, I.: The waterfront of Salerno: from product of urban regeneration to diffuser of sustainable social equity. In: Tedesco, C., Marchigiani, E. (eds.) Partecipazione, inclusione e gestione dei conflitti nei processi di governo del territorio, Atti della XXV Conferenza Nazionale SIU, Cagliari, 15–16 giugno 2023, vol. 07, pp. 1–10. Planum Publisher, Roma–Milano (2024)
3. Di Ruocco, I., D'Auria, A.: The multidimensional impact of Special Economic Zones in Campania Region. The TIA tool for land economic evaluation. BDC Bollettino Del Centro Calza Bini **23**(1), 133–155 (2023). https://doi.org/10.6093/2284-4732/10480
4. Mazzarino, M., Braidotti, L., Borruso, G.: A review of best practices to reduce the environmental footprint of port areas in the Adriatic region. In: Proceedings of the 2021 21st International Conference on Computational Science and Its Applications (ICCSA), pp. 168–173. IEEE (2021). https://arts.units.it/retrieve/00304741-a564-42d2-b80b-0d3be30a8539/2021_ICCSA_Best%2BPractices%2BAdriatic%2BPorts-Post_print.pdf
5. Puig, M., Darbra, R.M.: Innovations and insights in environmental monitoring and assessment in port areas. Curr. Opin. Environ. Sustain. **70**, 101472 (2024). https://doi.org/10.1016/j.cosust.2024.101472
6. Tijan, E., Jović, M., Aksentijević, S., Pucihar, A.: Digital transformation in the maritime transport sector. Technol. Forecast. Soc. Change **170**, 120879 (2021). https://doi.org/10.1016/j.techfore.2021.120879
7. Moya, I., et al.: Freight wagon digitalization for condition monitoring and advanced operation. Sensors **23**(17), 7448 (2023). https://doi.org/10.3390/s23177448
8. Parola, F., Risitano, M., Ferretti, M., Panetti, E.: Digital transformation in maritime ports: the future of smart port ecosystems. Technol. Forecast. Soc. Change **170**, 120888 (2021). https://doi.org/10.3390/fi16100350
9. Kuakoski, H.S., Lermen, F.H., Graciano, P., Lam, J.S.L., Mazzuchetti, R.N.: Marketing, entrepreneurship, and innovation in port management: trends, barriers, and research agenda. Marit. Policy Manag. **51**(7), 1517–1534 (2024). https://doi.org/10.1080/03088839.2023.2180548
10. Bhattacharjee, A., Chakraborty, S.: Global supply chain networks: roles of global partnerships and governance in supply chain performance. In: Global Partnerships and Governance of Supply Chain Systems, pp. 189–222. IGI Global, Hershey (2025). https://doi.org/10.4018/979-8-3693-6987-6.ch007

11. European Commission: Ethics guidelines for trustworthy AI. https://op.europa.eu/en/publication-detail/-/publication/d3988569-0434-11ea-8c1f-01aa75ed71a1. Accessed 30 Dec 2024
12. European Commission: The commission adopts the European sustainability reporting standards. https://finance.ec.europa.eu/news/commission-adopts-european-sustainability-reporting-standards-2023-07-31_en. Accessed 3 Dec 2024
13. Durán, C.A., Córdova, F.M.: Synergy and technology gaps in export logistics chains between a Chilean and a Spanish medium-sized port. Procedia Comput. Sci. **55**, 632–641 (2015). https://doi.org/10.1016/j.procs.2015.07.055
14. Risitano, M., Panetti, E., Ferretti, M., Parmentola, A.: The port community system as a local innovation system: a theoretical framework. Mercati e Competitività **1**, 97–118 (2017). https://doi.org/10.3280/mc2017-001006
15. Autosup Project. https://www.autosup-project.eu/. Accessed 12 Dec 2024
16. Henríquez, R., de Osés, F.X.M., Marín, J.E.M.: Technological drivers of seaports' business model innovation: an exploratory case study on the Port of Barcelona. Res. Transp. Bus. Manag. **43**, 100803 (2022). https://doi.org/10.1016/j.rtbm.2022.100803
17. Henríquez, R., Xavier Martínez de Osés, F., Martínez Marín, J.E.: IoT-driven business model innovation. In: Chao, K.M., Jiang, L., Hussain, O., Ma, S.P., Fei, X. (eds.) Advances in E-Business Engineering for Ubiquitous Computing. ICEBE 2019. Lecture Notes on Data Engineering and Communications Technologies, vol. 41, pp. 302–314. Springer, Cham (2020). https://doi.org/10.1007/978-3-030-34986-8_22
18. United Nations: Transforming our world: the 2030 agenda for sustainable development. https://sustainabledevelopment.un.org/content/documents/21252030%20Agenda%20for%20Sustainable%20Development%20web.pdf. Accessed 30 Dec 2024
19. Caldwell, S.: Empirical decision-making tools as applied to seaports in the industry 4.0 paradigm. Doctoral dissertation, Liverpool John Moores University (2024). https://researchonline.ljmu.ac.uk/id/eprint/24910
20. Brümmerstedt, K., Beek, M.V., Münsterberg, T.: Comparative analysis of synchromodality in major European seaports. In: Kersten, W., et al. (eds.) Digitalization in Maritime and Sustainable Logistics, HICL, vol. 24, pp. 59–76. epubli GmbH, Berlin (2017). https://hdl.handle.net/10419/209326
21. Kringelum, L.T.B.: Reviewing the challenges of port authority business model innovation. World Rev. Intermodal Transp. Res. **8**(3), 265–291 (2019). https://doi.org/10.1504/WRITR.2019.102371
22. Acciaro, M., Sys, C.: Innovation in the maritime sector: aligning strategy with outcomes. Marit. Policy Manag. **47**(8), 1045–1063 (2020). https://doi.org/10.1080/03088839.2020.1737335
23. Zong, Z., Guan, Y.: AI-driven intelligent data analytics and predictive analysis in Industry 4.0: transforming knowledge, innovation, and efficiency. J. Knowl. Econ., 1–40 (2024). https://doi.org/10.1007/s13132-024-02001-z
24. Shaikh, M.Z., et al.: State-of-the-art wayside condition monitoring systems for railway wheels: a comprehensive review. IEEE Access **11**, 13257–13279 (2023). https://doi.org/10.1109/ACCESS.2023.3240167
25. Neffke, F., Henning, M., Boschma, R.: How do regions diversify over time? Industry relatedness and the development of new growth paths in regions. Econ. Geogr. **87**(3), 237–265 (2011). https://doi.org/10.1111/j.1944-8287.2011.01121.x
26. Infomare: Traffico porto Trieste. https://www.informare.it/news/gennews/2025/20250154-porto-Trieste-traffico-Y-2024.asp. Accessed 27 Mar 2025
27. Port System Authority of the Eastern Adriatic Sea: Port network authority of the Eastern Adriatic Sea – Port of Trieste. https://ipcsa.international/about/members/members-europe-and-north-america/port-network-authority-of-the-eastern-adriatic-sea-port-of-trieste/. Accessed 27 Mar 2025

28. Charpentier, P., Chaxel, F., Krommenacker, N., Bombardier, V., Seguel, F.: Pervasive digital twin for pi-containers: a new packing problem. Sensors **21**(23), 7999 (2021). https://doi.org/10.3390/s21237999
29. Montreuil, B., Meller, R.D., Ballot, E.: Physical internet foundations. In: Borangiu, T., Thomas, A., Trentesaux, D. (eds.) Service Orientation in Holonic and Multi Agent Manufacturing and Robotics. Studies in Computational Intelligence, vol. 472, pp. 151–166. Springer, Heidelberg (2013). https://doi.org/10.1007/978-3-642-35852-4_10
30. ITF: Information sharing for efficient maritime logistics. https://www.itf-oecd.org/sites/default/files/docs/information-sharing-maritime-logistics.pdf. Accessed 6 Jan 2025
31. Moulaert, F., Sekia, F.: Territorial innovation models: a critical survey. Reg. Stud. **37**(3), 289–302 (2003). https://doi.org/10.1080/0034340032000065442
32. Notteboom, T., Rodrigue, J.-P.: Maritime container terminal infrastructure, network corporatization, and global terminal operators: implications for international business policy. J. Int. Bus. Policy (2022). https://doi.org/10.1057/s42214-022-00142-z
33. Ostrom, E.: Understanding Institutional Diversity. Princeton University Press, Princeton (2005)
34. Cahoon, S., Pateman, H., Chen, S.L.: Regional port authorities: leading players in innovation networks? J. Transp. Geogr. **27**, 66–75 (2013). https://doi.org/10.1016/j.jtrangeo.2012.06.015
35. Witte, P., Slack, B., Keesman, M., Jugie, J.H., Wiegmans, B.: Facilitating start-ups in port-city innovation ecosystems: a case study of Montreal and Rotterdam. J. Transp. Geogr. **71**, 224–234 (2018). https://doi.org/10.1016/j.jtrangeo.2017.03.006
36. Boschma, R.: Proximity and innovation: a critical assessment. Reg. Stud. **39**(1), 61–74 (2005). https://doi.org/10.1080/0034340052000320887
37. Notteboom, T., Rodrigue, J.P.: Containerisation, box logistics and global supply chains: the integration of ports and liner shipping networks. Marit. Econ. Logist. **10**, 152–174 (2008). https://doi.org/10.1057/palgrave.mel.9100196
38. Stam, F.C.: Why butterflies don't leave; locational evolution of evolving enterprises (2003). https://doi.org/10.1111/j.1944-8287.2007.tb00332.x
39. Permala, A., Rantasila, K., Porthin, M., Hinkka, V., Eckhardt, J., Leonardi, J.: Multi-criteria evaluation method for freight logistics innovations. IET Intell. Transp. Syst. **9**(6), 662–669 (2015). https://doi.org/10.1049/iet-its.2014.0187
40. Pagano, P., Antonelli, S., Tardo, A.: C-Ports: A proposal for a comprehensive standardization and implementation plan of digital services offered by the "Port of the Future." Comput. Ind. **134**, 103556 (2022). https://doi.org/10.1016/j.compind.2021.103556
41. De Martino, M.: Value creation for sustainability in port: perspectives of analysis and future research directions. Sustainability **13**(21), 12268 (2021). https://doi.org/10.3390/su132112268
42. Kundu, P., Darpe, A.K., Singh, S.P., Gupta, K.: A review on condition monitoring technologies for railway rolling stock. In: Proceedings of the PHM Society European Conference, Philadelphia, PA, USA, 24–27 September 2018. https://doi.org/10.36001/phme.2018.v4i1.250
43. dos Santos, M.C., Pereira, F.H.: Development and application of a dynamic model for road port access and its impacts on port-city relationship indicators. J. Transp. Geogr.Geogr. **96**, 103189 (2021). https://doi.org/10.1016/j.jtrangeo.2021.103189