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Chapter

Policy Learning in the Age of Digital Transformation: Lessons from 5G and Beyond

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Abstract

Modern seaports are parts of the global supply chain and act as points that influence economic performance and environmental sustainability. The fast growth of transformation, which uses technologies such as 5G and artificial intelligence (AI), will reshape traditional logistics operations. Digital transformation will improve efficiency, strengthen safety, and cut emissions. The implementation of these technologies does not depend solely on how mature the technology is. The implementation of these technologies also requires public authorities, port operators, and private sector innovators to get involved and work together. The chapter looks at how the 5G-LOGINNOV project tackled the challenge by integrating two frameworks, namely the collaborative governance regime (CGR) and the Go, Uniform, Evaluate, Solve, Test (GUEST) methodology. The proposed approach creates a step-by-step, open process that repeats itself. The process allows stakeholders to spot barriers, try solutions, and co-develop planned regulatory and policy responses that fit the challenges of seaport ecosystems. Drawing on evidence from three European testbeds – Athens–Piraeus, Hamburg, and Koper – the chapter explains that coordinated policy learning can help the transition. The chapter explains that the transition moves the seaport ecosystem toward a smart, resilient, and sustainable seaport ecosystem in the age of transformation.

Keywords: policy learning, digital transformation, 5G and artificial intelligence, governance frameworks, maritime ports

1. Introduction

The digital change in transport and logistics is a shift that affects global trade and industry. Nowadays, the seaports link ships with land transport and play a role in the digital change. The new technologies, like 5G, Internet of Things (IoT), artificial intelligence (AI), edge computing, and automation, bring important benefits to port operations.

Technological innovation does not, by itself, guarantee a rollout. The gap between readiness, the regulatory rules, the organizational needs, and the societal expectations often slows adoption. The 5G-LOGINNOV project proposed to combine the Go, Uniform, Evaluate, Solve, Test (GUEST) methodology – a step-by-step process for innovation and business modeling – with the collaborative governance regime (CGR). The CGR represents a governance framework for multi-stakeholder coordination.

This chapter is based on the work done in 5G-LOGINNOV and addresses two main objectives:

O#1: To propose common policy frameworks and recommendations supporting the deployment of 5G technologies in ports and their hinterlands.

O#2: To demonstrate a replicable governance model capable of aligning technological innovation with broader public-policy objectives in complex multi-actor systems.

The above objectives are supported by empirical evidence from three operational testbeds:

Hamburg used 5G to improve traffic management in the hinterland and reduce CO_2 emissions.

Koper uses private 5G networks to enable applications beyond Industry 4.0 and port automation.

Athens–Piraeus used AI video analytics and connected assets to support maintenance and improve safety.

By looking at the testbeds, this chapter provides a governance–innovation methodology that ties digital transformation and the adoption of disruptive technologies with policy learning, regulatory adaptation, and multi-actor collaboration.

2. State of the art

This section presents the state of the art by examining perspectives on 5G technology in seaport environments, outlining gaps in the existing literature, and emphasizing the role of governance and policy learning in the transformation.

2.1 Technological perspectives on 5G in seaport environments

The introduction of 5G networks in seaports has drawn a lot of interest from researchers and industry [1–3]. The new network features include ultra-reliable low-latency communications (URLLC), high-bandwidth transmission, network slicing, and multi-access edge computing (MEC), enabling applications such as:

- Remote control of cranes and automated guided vehicles (AGVs).
- Digital twins of port operations.
- High-resolution video surveillance and AI-based threat detection.
- Real-time tracking of containers and vessels.

- Autonomous or platooned truck movements.
- Enhanced environmental monitoring through IoT sensors.

These capabilities provide opportunities to enhance transparency, resilience, and safety across port operations.

2.2 Gaps in existing literature

Despite important technological progress, the existing research still focuses too much on technical feasibility. The key gaps include the following:

- Limited assessment of economic viability and sustainable business models for 5G-enabled port solutions [4].
- Insufficient attention to governance structures, collaborative mechanisms, and regulatory alignment.
- Fragmentation of policies related to spectrum allocation, cross-border connectivity, and infrastructure investment.
- Lack of standardization across interfaces, equipment, and 5G deployment practices in maritime contexts.

The gaps block the transition and keep the seaports from becoming scalable real-world deployments [5].

Complimentary experiments in Bristol and Riga tested container tracking with sensors, and the experiments also tested drones for safety and security. The experiments confirmed that network slicing, edge computing, and private 5G networks all work for seaport ecosystems [6–8].

Studies highlight the importance of coordinated policies for spectrum allocation, incentives for infrastructure investment, and cross-border teleoperation, but detailed regulatory analyses specific to seaports are insufficient [9, 10].

2.3 Importance of governance and policy learning for digital transformation

From the three testbeds' experience, a successful digital transformation in ports needs more than technology deployment. A successful digital transformation in ports also needs alignment across the following:

- Policy and regulation.
- Organizational structures.
- Interoperability frameworks.
- Long-term investment strategies.
- Capacity building and skills development.

The literature is starting to explore the need for governance frameworks capable of handling many different parts of a system. The governance frameworks must bring together technology, social and economic considerations, and rules. Detailed, real-data studies that focus on port ecosystems are still few.

The 5G-LOGINNOV project addressed these gaps by combining innovative methodologies with governance frameworks to create policy recommendations based on empirical evidence. Addressing the gaps is needed to speed up the development of 5G-based seaports and provides clear guidance to policymakers and practitioners [11]. Connecting potential with governance structures and investment strategies makes the outcome possible.

3. Real-world innovation labs: 5G-LOGINNOV testbeds

The 5G-LOGINNOV project implemented 5G solutions in three operational seaport locations: Athens–Piraeus, Hamburg, and Koper. These three testbeds act as real-world laboratories that demonstrate how 5G capabilities can support advanced logistics, safety, and sustainability applications to accelerate digital transformation. Together, the three experimental transformation deployments demonstrated that context-specific 5G applications can greatly improve operational efficiency, safety, and sustainability in advanced seaport logistics [9].

3.1 Athens–Piraeus testbed

The team deployed the testbed at the Piraeus Container Terminal, which included:

- A private 5G network.
- Edge computing capabilities.
- AI-driven video analytics.
- Connected assets, including cranes, yard trucks, and IoT sensors.

These components enable real-time monitoring and early detection of anomalies, improve predictive maintenance, enable real-time tracking, and improve security in the port ecosystem. The components also support mission-critical operations that need low latency and high uplink capacity.

3.2 Hamburg testbed

The Hamburg pilot addressed smart mobility and environmental sustainability by improving port-hinterland connectivity, traffic management, and emission reduction using 5G-based solutions. The Hamburg pilot deployed the following:

- Floating truck emission sensors.
- Dynamic traffic management systems.

- Automated truck platooning.
- Real-time data exchange among operators, infrastructure managers, and logistics stakeholders.

The use of 5G networks provides communication, cuts emissions, and is making traffic flow better. The operational improvements cut carbon emissions, and the operational improvements are aligning the city's mobility and decarbonization plans.

3.3 Koper testbed

Koper focused on industrial networks by deploying the following:

- Standalone (SA) and non-standalone (NSA) 5G infrastructures.
- Network slicing.
- Drone-based surveillance systems.
- AI-assisted video analytics.
- 5G-enabled industrial IoT devices.

The Koper testbed validated the ability of custom networks to provide guaranteed quality of service, improve asset visibility, support mission-critical operations, enhance security protocols, and support port automation. The Koper testbed showcases Koper as a model for high-performance smart port operations [12, 13].

Table 1 compares the three seaports and presents the technologies that were used, the main use cases, and the results that were observed.

4. Methodological design

To analyze the relationship between innovation, governance, and policy in port environments, 5G-LOGINNOV used an integrated method that combined the CGR and the GUEST methodology [14]. The CGR framework provides a theory for encouraging the ongoing interaction of stakeholders, fostering trust between them, and facilitating collective problem-solving. The CGR framework also aligns with the findings of established studies on policymaking in contexts where institutions and organizations depend on each other. The GUEST methodology follows a step-by-step process for business modeling and innovation management. The GUEST methodology also allows for comparing use cases and extracting results that are significant for policy. The next sections present the integrated framework and the digital transformation that the GUEST methodology developed in 5G-LOGINNOV, which can serve as a showcase for other 5G projects.

Port/ testbed	Technologies deployed	Key use cases	Outcomes/benefits
Athens (Piraeus Container Terminal)	The private 5G network provides wireless connectivity The edge large-scale computing runs tasks close to the source The AI-based video analytics watches video and finds patterns The connected port assets include yard trucks, cranes, and IoT devices	Real-time asset tracking, predictive maintenance, safety-critical operations	Mission-critical applications with ultra-low latency, improved operational efficiency, and augmented security measures
Hamburg	5G-enabled networks, floating truck emission sensors, automated truck platooning, dynamic traffic management systems	Optimizing hinterland connectivity, traffic management, carbon reduction	Real-time stakeholder data exchange; operational efficiency improvements; measurable reductions in emissions; alignment with smart mobility and decarbonization goals
Koper	5G standalone (SA) and non-standalone (NSA) networks, network slicing, AI-assisted video analytics, drone monitoring, industrial 5G IoT devices	Logistics automation, port security monitoring, beyond Industry 4.0 applications	Assured quality of service; strengthened asset visibility; automation of port operations; model for secure, high-performance smart port operations

Table 1.
The comparative analysis and an overview of the three seaports.

4.1 Integrated CGR–GUEST framework

The method used an integrated methodological approach in which the CGR framework is coupled with the GUEST methodology. The coupling enables the following:

- Structured multi-stakeholder engagement.
- Systematic business modeling.
- Standardized evaluation processes.
- Evidence-based policy formulation.
- Iterative cocreation and validation of recommendations.

CGR ensures governance structure alignment and multi-stakeholder relationships development, while GUEST provides the tools for managing innovation to transform shared visions into tested outcomes.

4.2 Collaborative governance regime

The CGR framework is designed to promote iterative engagement among stakeholders, such as government representatives, private sector actors, and civil society organizations.

CGR organizes the multi-stakeholder collaboration around three linked components as follows:

- Principled engagement: Stakeholders have organized workshops and iterative discussions. The GUEST methodology provides tools to support communication across diverse environments and reduces misunderstandings by using standardized data and clear value definitions.

- Shared motivation: The transparent processes and the continuous feedback help develop trust, mutual understanding, and shared commitment. GUEST's standardized approach reinforces trust, reinforces understanding, and reinforces shared commitment.

- Capacity for action: Capacity for joint action is when the people involved coordinate resources, take on leadership roles, and possess the working capacities to implement a common solution.

- The three components act as a reinforcing cycle, enabling long-term collaboration, helping us learn about policy and creating shared value, and giving constructive feedback.

4.3 The GUEST methodology

The main goal of the proposed methodology is to provide an easy-to-use approach that guides users through the decision-making process and facilitates the adoption of 5G-based solutions [15]. The Go, Uniform, Evaluate, Solve, Test methodology supports innovation under uncertainty, in rapidly changing technology environments and disruptive innovation scenarios. Politecnico di Torino developed GUEST [16–19]. Its characteristics include the following:

- Emphasis on structured business modeling.

- Standardized templates enabling comparability across pilots.

- Inclusion of participants with varying expertise.

- Integration of market analysis with technological assessment.

- Support for early identification of risks and barriers.

This approach is particularly critical in the early stages of innovation, where unsuccessful outcomes often surpass successful ones, allowing stakeholders to identify components that require close monitoring [20].

The GUEST approach draws on the Business Model Canvas [21] and the Lean Startup principles by implementing those concepts in multi-actor complex systems (MACS). The GUEST approach also rests on the Technology–Organization–Environment framework and on socio-technical transitions. The GUEST approach receives feedback and real-world application in blockchain consortia and other sectors [22–25].

4.4 Application in 5G-LOGINNOV

The GUEST methodology was widely applied in the 5G-LOGINNOV project to align the innovation with the business objectives and the policy objectives.

The integrated framework supported the following:

- Review of logistics roadmaps and formulation of the two main policy frameworks.
- Classification of challenges into a harmonized taxonomy for organizing barriers and opportunities in 5G-based logistics innovation.
- Business modeling involving startups, small- and medium-sized enterprises (SMEs), port authorities, and technology partners facilitated the alignment of stakeholder expectations with real needs during business model development.
- Prioritization and refinement of recommendations: The partner prioritization exercises identified the actions with the most impact. Refinement of recommendations created an initial portfolio of 64 recommendations, 32 per policy framework. Prioritization and refinement of recommendations grouped the recommendations into six challenge categories.
- Validation through workshops with stakeholders and networks ensured that the technical feasibility and policy relevance were appropriate for authorities and the European Union (EU).

The engagement also brought in five startups that the 5G-LOGINNOV open call selected, establishing new project partners, and the solutions addressed viability and ecosystem integration.

The proposed integration of the CGR and the GUEST methodology provided three results as follows:

(1) Evidence-based policy recommendations, owned by stakeholders, guarantee legitimacy and acceptance of the suggestions.

(2) Standardized results across different pilot projects, allowing for comparability across cases.

(3) A replicable and scalable methodology for integrating technology and policies beyond 5G logistics.

In 5G-LOGINNOV, by consolidating the results of surveys, interviews, workshops, and collaborations with external organizations, the study produced a final set of tailored recommendations for public authorities and the European Commission. These recommendations provided concrete guidance to support the adoption of 5G in transport and logistics and to address sectoral challenges through coherent, evidence-based policy measures. The overall process is depicted in **Figure 1.**

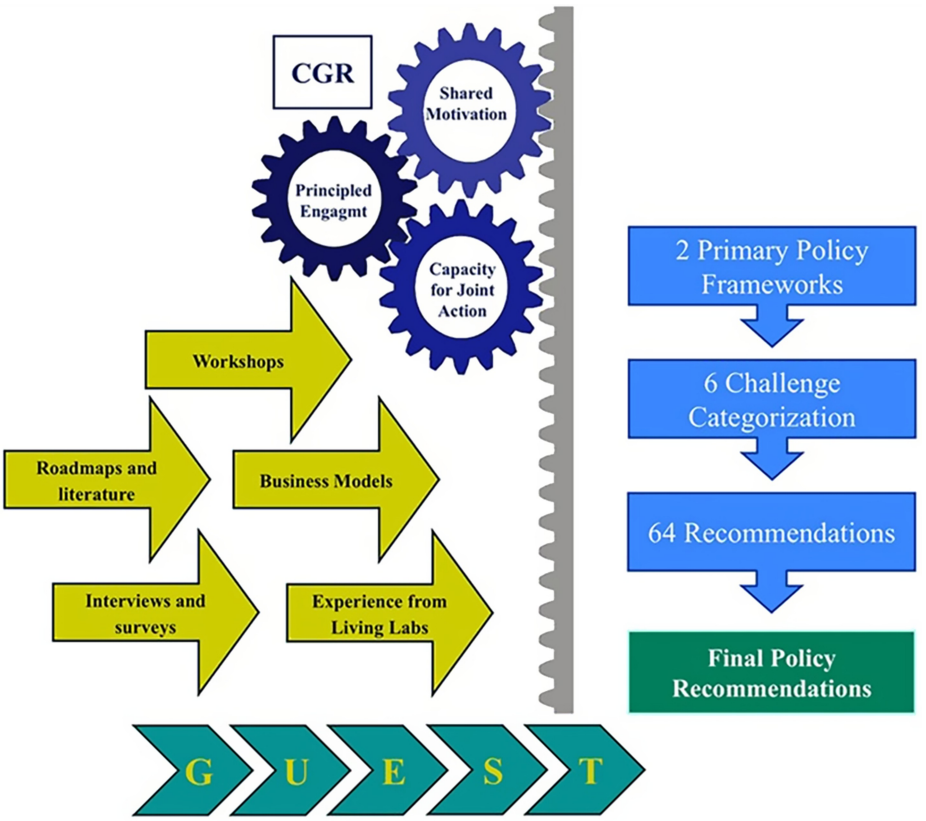


Figure 1.
The methodological framework of our research (adapted from [11]).

5. Results

The CGR-GUEST integrated framework in 5G-LOGINNOV started with an assessment of the logistics roadmaps that already exist. The ERTICO 2025 Logistics Roadmap was the relevant reference that pointed out three priorities for the sector: full digitalization, automation, and interoperability between transport and logistics systems. Building on this foundation, the workshops explored how the results of the 5G-LOGINNOV project could align with and strengthen these strategic objectives.

5.1 Policy frameworks

Stakeholders pointed out that 5G-based AI for logistics is important, complemented by advanced green light speed advisory systems, collision avoidance mechanisms, and remote telemonitoring solutions. The mind map depicts the links between the concepts (see **Figure 2**), organizing the conclusions into two policy frameworks that support the recommendations that go to authorities and the European Commission:

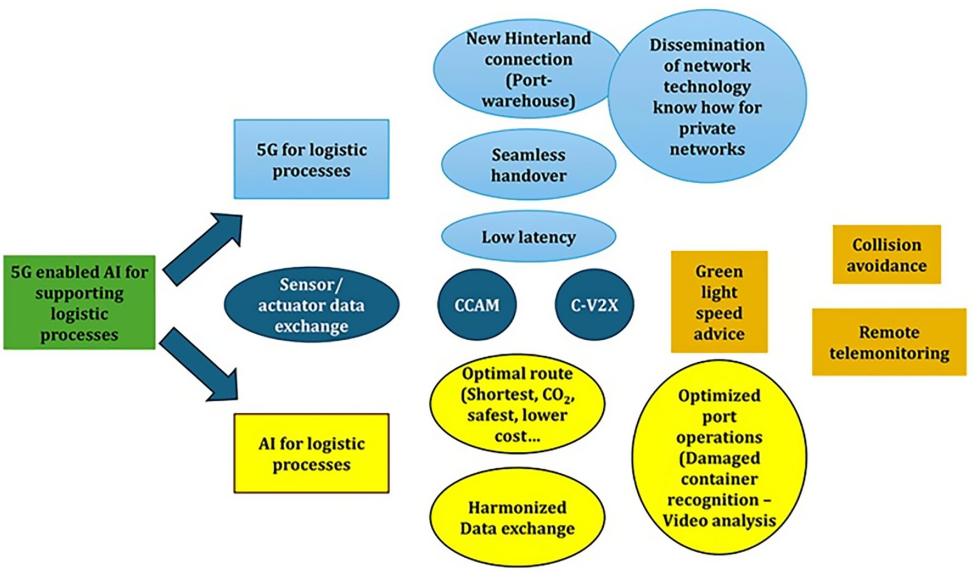


Figure 2.
The developed mind map illustrates key relationships among proposed concepts (adapted from [11]).

(1) Prioritize the deployment of 5G networks in Trans-European Transport Network (TEN-T) corridors and seaport areas.

(2) Promote AI research, development, and deployment to optimize logistics and port operations.

These frameworks support efficiency, safety, sustainability, and interoperability, following the emerging Industry 6.0 principles.

The proposed approach aligns with the pillars of the emerging Industry 6.0, which goes beyond automation toward system integration by including cognitive ability and human and machine working together as follows:

- Resilience: Strengthening operational continuity in ports and hinterland networks, exemplified by the ports of Koper and Hamburg.
- Human-centricity: Ensuring safer working conditions for transport drivers, road users, and port staff.
- Sustainability: Contributing to measurable reductions in CO_2 emissions.
- Hyper-intelligent systems: AI-powered decision-making through machine learning and neuromorphic computing.
- Full human–AI integration: Facilitating cognitive interaction between humans and machines, encouraging seamless collaboration between biological and digital entities.

- Quantum computing: Integrating quantum technologies into industrial applications to deliver unprecedented computing power and problem-solving capabilities.

- Ubiquitous connectivity and decentralized networks: Ubiquitous connectivity and decentralized networks set up distributed networks that link the devices, the systems, and the industrial infrastructure. Ubiquitous connectivity and decentralized networks use blockchain or quantum networks to make the connections smooth.

- Global and environmental awareness: Leveraging global AI ecosystems to monitor and manage environmental, social, and governance (ESG) objectives.

5.2 Implementation challenges

In 5G-LOGINNOV, a structured process to identify the barriers preventing the two policy frameworks from being utilized was implemented. The process employed the GUEST standardization tools within the CGR framework and formulated six categories of implementation challenges. Each implementation challenge highlights a problem or obstacle encountered by the project. The categories and their brief descriptions are provided in **Table 2.**

Each category reflects the challenges faced in the three testbeds.

5.3 Development and validation of recommendations

The Solve and Test phases of the GUEST methodology made an initial set of 64 recommendations, evenly distributed across the two policy frameworks and structured into the six challenge categories that were already defined.

The recommendations came from an analysis of testbeds' business models. The analysis highlighted the value propositions for each use case. The partners used

Challenge [C#]	**Description**
C#1: Technical gaps	Insufficient 5G connectivity and incompatibilities with existing infrastructure
C#2: Infrastructure and Installation gaps	Obstacles caused by the incompatibility of new systems with pre-existing infrastructure and systems
C#3: Regulatory gaps	Included cases where installation and operation conflicted with existing regulations, requiring formal approvals or navigating through legislative loopholes and ambiguous rules
C#4: Administrative gaps	Requirements for certifications, official registrations, and compliance testing are needed
C#5: Training and expertise gap	Lack of qualified technical personnel to install the equipment and difficulties in understanding and managing the technology
C#6: Business models gaps	Reluctance of customers or entrepreneurs to invest in the project, often due to uncertain or poorly defined business models

Source: Adapted from the study by Catana et al. [11].

Table 2.
Summary of gaps identified.

Solution Canvas analyses and survey feedback to prioritize the proposals. The partners identified the important actions, and the questionnaire captured the partners' perspectives on the challenges of implementing 5G solutions in ports and hinterland networks. The questionnaire also asked about 5G operator engagement and capacity-building measures for 5G infrastructure. The contributions were integrated. This integration gave us a set of policy recommendations, which were included in the CGR governance cycle. The CGR governance cycle ensured the policy recommendations matched the goals of the consortium. The consortium could see the policy recommendations and agree on them.

External stakeholders checked the recommendations and further improved them. The 5G-LOGINNOV consortium organized two workshops in March 2023 and May 2023, where they also interviewed representatives of ALICE, FENIX, and CCAM. The workshops and the interviews provided insight into the implementation challenges and potential solutions. The first workshop examined the 5G infrastructure public–private partnership (5G-PPP) and the implementation gaps identified by the 5G-LOGINNOV framework. The first workshop produced recommendations for public authorities and the European Commission. The second workshop brought together a group of stakeholders who examined the two policy frameworks created by the project and further identified strategies to support the adoption of 5G and AI in European seaports and hinterland networks.

The information from these workshops and interviews was consolidated to enhance the robustness, feasibility, and policy relevance of the final recommendations.

5.4 Final recommendations

The team gathered the findings of the 5G-LOGINNOV project using the GUEST-CGR methodology. The team validated the findings with external stakeholders. The findings led the team to develop a set of *eight recommendations* [R#]. The recommendations (Rr#1–-Rr#8) address the challenges that the three testbeds identified. The recommendations provide guidance to authorities, regulators, equipment manufacturers, and research communities. The eight final recommendations are as follows:

R#1: Ensure reliable low-latency performance for mission-critical applications. Reliable low latency is essential for the operation of many mission-critical applications. To address the low-latency challenge, work closely with mobile network operators (MNOs). Work closely with MNOs to address license limits, use network segmentation tools, and make the rules easier. Also, deploy mobile edge computing. Deploy mobile edge computing by placing data hubs at network points such as Hamburg. Data hubs at Hamburg can cut transmission delays and improve system response times.

R#2: Facilitate compatibility between 5G infrastructure and existing port systems: Structural and operational constraints have slowed the deployment of 5G hardware into port facilities. These constraints limit where equipment can be placed and how the equipment can be powered. Engineers have identified cranes as suitable locations for installing transponders; however, cranes have created challenges. Cranes often require Wi-Fi systems that provide limited coverage and performance. Stakeholders must transition to an updated

infrastructure. Recommended measures include the establishment of voluntary guidelines and standards for equipment modernization, as well as incentives for port operators to adopt 5G-compatible equipment. Encouraging competition and innovation in the 5G private market is also essential to sustain technological progress.

R#3: Establish harmonized and interoperable standards: The lack of harmonized interfaces creates fragmented solutions. The lack of harmonized technical interfaces forces ad hoc agreements with each provider. The lack of harmonized interfaces blocks effective integration. The recommendation is to create a Technical Standards Committee. The Technical Standards Committee will define interoperable standards for 5G deployment in ports and inland areas. The Technical Standards Committee can set up certification processes. The Technical Standards Committee can offer incentives for adoption. The Technical Standards Committee can launch cooperation initiatives. The Technical Standards Committee can run training programs. I expect the policies will simplify operations. The policies will cut integration costs and increase competition in the market.

R#4: Improve accessibility and quality of AI tools: Project partners have faced challenges in obtaining the right AI software for their planned projects. The demand for AI tools keeps growing, but affordable and good-quality AI tools are still scarce. The scarcity of AI tools limits ideas and slows adoption. To address this gap, we need to invest in research and development. We need to revise licensing rules and intellectual property policies. We need to establish compatibility standards and build interfaces for AI tools. We recommend promoting open-source initiatives. We recommend that open-source initiatives receive institutional resources. We also recommend creating a platform for sharing AI toolkits and resources.

R#5: Support development and use of AI models such as large language Models (LLMs) and Large Multimodal Models (LMMs). The approach will make AI development open to people. The approach will allow nonexperts to take part in AI implementation. To make this happen, we need training datasets [14, 26]. We need ethical guidelines. We need frameworks that ensure the use of generative AI models remains responsible and effective. I think AI literacy needs investment. I think AI communities need engagement. The investment will help align the technologies with the needs of the industry and society.

R#6: Deploy cloud environments that fit port operations: Security, privacy, and infrastructure constraints challenge the integration of AI tools into seaport ICT systems. One example of a constraint is the restriction on modifications to cranes. Adopt cloud environments. A dedicated cloud environment, such as infrastructure as a service (IaaS), built for seaport operations, can enable deployment while respecting the operational boundaries. Secure cloud environments protect the port and keep seaport operations safe.

R#7: Strengthen cooperation with equipment manufacturers: There is a need to strengthen cooperation with equipment manufacturers. Powered logistics operations often require devices such as IoT sensors and cameras on cranes. The equipment ownership and the manufacturers' rules limit what we can do. That is why we need to start working with equipment manufacturers. We need to collaborate with equipment manufacturers to create flexible, low-impact solutions that align with AI services while ensuring the safety of important equipment.

R#8: Create a combined knowledge repository for 5G applications in ports. The knowledge repository will bring together research findings, case studies, and best

Recommendation	Key issue addressed	Proposed actions
R#1: Ensure reliable ultra-low latency performance for mission-critical applications	Unreliable low-latency performance in commercial 5G deployments	Engage mobile network operators to address licensing constraints, implement network segmentation, simplify regulatory frameworks, and deploy mobile edge computing infrastructure
R#2: Facilitate compatibility between 5G infrastructure and existing port systems	Challenges in integrating 5G hardware with existing port infrastructure, including dependencies on legacy systems	Develop guidelines and standards while encouraging investment in 5G-compatible equipment and infrastructure
R#3: Establish harmonized and interoperable technical standards	Lack of unified technical standards hindering seamless system integration	Establish a Technical Standards Committee to define open standards, implement certification processes, promote early adoption, improve international collaboration, and facilitate specific training programs
R#4: Improve accessibility and quality of AI software tools	Limited availability of high-quality, affordable AI solutions for operational applications	Intensify research and development efforts, support open-source initiatives, define interoperability standards, reform intellectual property and licensing frameworks, ensure user-centric interfaces, and develop a centralized open-source platform
R#5: Support responsible development and adoption of generative AI models	Robust training datasets, develop ethical guidelines	Implement standardized protocols, deploy customized infrastructure-as-a-service solutions, and ensure secure and interoperable integration of AI applications
R#6: Deploy secure cloud environments tailored to port operations	Promote collaborative frameworks; implement reliable security solutions	Continued investment in AI and engagement with AI communities align these technologies with the needs of industry and society
R#7: Strengthen cooperation with equipment manufacturers	Limitations on device location and ownership, requiring neutral and nonintrusive design solutions	Promote early collaboration with equipment manufacturers to co-develop adaptable, nonintrusive solutions aligned with AI service requirements
R#8: Create a consolidated knowledge repository for 5G applications in ports	Dispersed and incomplete access to 5G knowledge, tools, and resources for port operations	Create a centralized knowledge platform that consolidates research, case studies, and best practices to support stakeholder decision-making

Source: Adapted from the study by Catana et al. [11].

Table 3.
Final recommendations for 5G deployment in ports and hinterland areas.

practices so that informed decision-making can be easier. The knowledge repository will support decision-making and help the adoption of technologies in logistics.

The above eight recommendations are summarized in **Table 3**, which highlights the main challenges observed during the 5G-LOGINNOV project implementation and presents the proposed actions.

5.5 Added value of the CGR–GUEST integration

The integration of the CGR and GUEST added significant value to the 5G-LOGINNOV project results. The combined approach allowed us to work collaboratively to create all recommendations with stakeholders and tie the recommendations to business models, which made them more legitimate and useful. 5G-LOGINNOV established feedback loops between the governance-oriented CGR framework and the execution-oriented GUEST methodology. These continuous feedback loops accelerated the process, moving the work swiftly from identifying challenges to building, testing, and agreeing on practical solutions.

6. Conclusions

This chapter demonstrated that the digital transformation in the seaport ecosystems is as much a governance challenge as it is a technology challenge. By combining the CGR with the GUEST methodology, the 5G-LOGINNOV project provides the following:

- A replicable governance model.
- A structured innovation process.
- Evidence-based, stakeholder-validated policy recommendations.
- Practical insights applicable beyond the maritime domain.

The research shows the importance of integrated approaches that link innovation potential with institutional capacity, regulatory changes, and cooperation among many actors.

5G-LOGINNOV project contributed to the larger discussion about digital transformation in critical infrastructures, demonstrating that strong governance frameworks and rigorous methods are as important as innovation for successful adoption, especially true in multi-stakeholder settings.

5G-LOGINNOV pointed out some limitations. The evidence comes mainly from EU-funded projects. The integrated approach may not work the same way in other regulatory, cultural, or market settings, and we need to test the integrated approach. A second limitation is timing; the full measure of the effectiveness of the proposed policy frameworks is not yet available because the proposed policy frameworks rely on measures, and the innovative measures have not yet been put into practice.

Future research can examine how governance and innovation frameworks adapt to regions outside Europe. Future research can also explore how the barriers to 5G rollout evolve over time and assess the impact of policy advice. Another research avenue is to investigate how LLMs and LMMs can make AI applications for seaport operations more accessible. Large language models and LMMs must remain human-centric. Additionally, LLMs and LMMs require robust datasets and must align with industry needs to facilitate broader adoption.

Abbreviations

AI	Artificial intelligence
AGVs	Automated guided vehicles
CGR	Collaborative governance regime
ESG	Environmental, social, and governance
GUEST	Go, Uniform, Evaluate, Solve, Test
IoT	Internet of things
IaaS	Infrastructure as a service
LLMs	Large language model
LMMs	Large multimodal model
MACS	Multi-actor complex systems
MEC	Multi-access edge computing
NSA	Non-standalone
SA	Standalone
TEN-T	Trans-European Transport Network
O#	Objective
5G-PPP	5G infrastructure public–private partnership
MNOs	Mobile network operators
[R#]	Recommendation no
URLLC	Ultra-reliable low-latency communications

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References

[1] Dolgui A, Ivanov D. 5g in digital supply chain and operations management: Fostering flexibility, end-to-end connectivity and real-time visibility through internet-of-everything. International Journal of Production Research. 2022;**60**(2):442–451

[2] Torsoli G, Stracca S, Puleri M, et al. Beyond 5g-assisted automatic guided vehicles in seaport environments. In: 2023 IEEE International Conference on Communications Workshops (ICC Workshops). IEEE; 2023. p 1038–1043

[3] Yigit Y, Nguyen LD, Ozdem M, et al. Twinport: 5g drone-assisted data collection with digital twin for smart seaports. Scientific Reports. 2023;**13**:12310

[4] T-Systems, Tech4U, Continental. KPI set for evaluating the environmental impact of using 5G in data exchange for traffic management outside the port and the hinterland. Zenodo. 2024. DOI: 10.5281/zenodo.10204637

[5] Slamnik-Kriještorac N, Camelo M, Chang CY, et al. Ai- empowered management and orchestration of vehicular systems in the beyond 5g era. IEEE Network. 2023;**37**:305–313

[6] Andriani OF, Nashiruddin MI, Adriansyah NM: 5g private network assessment for port industrial area: Study case in port of Tanjung Priok. In: 2023 IEEE International Conference on Communication, Networks and Satellite (COMNETSAT). IEEE, 2023; 584–590

[7] Charpentier V, Slamnik-Kriještorac N, Landi G, et al. Paving the way towards safer and more efficient maritime industry with 5g and beyond edge computing systems. Computer Networks. 2024;**250**:110499

[8] Ferro E, Gennaro C, Nordio A, et al. 5g-enabled security scenarios for unmanned aircraft: Experimentation in urban environment. Drones. 2020;**4**:22

[9] Catana E, Basaras P, Willenbrock R. Enabling innovation in maritime ports and the need of the 6g candidate technologies: 5G-LOGINNOV showcase. In: 2023 IEEE 9th World Forum on Internet of Things (WF-IoT). IEEE; 2023. p. 1–5

[10] Trichias K, Landi G, Seder E, et al. Vital-5g: Innovative network applications (NetApps) support over 5g connectivity for the transport & logistics vertical. In: 2021 Joint European Conference on Networks and Communications & 6G Summit (EuCNC/6G Summit). IEEE; 2021. p. 437–442

[11] Catana E, Merlo F, Guido Perboli. Governing digital transformation in ports: Policy learning from the 5G-LOGINNOV project. Open Research Europe. 2025. 1of13

[12] 5G-LOGINNOV Consortium: 5G-LOGINNOV project web site. 2021; [Accessed: 2025-August-21]

[13] 5G-LOGINNOV Consortium. Deliverable 2.3: Development and Deployment Final Report. Technical Report. 5G-LOGINNOV Consortium (Horizon 2020, GA No. 957400). 2024; [Accessed: 2024-January-08]

[14] Cortés A, Delgado G, García S. Zenodo. 2024. [Accessed: 2025-February-4]

[15] Fadda E, Gobbato L, Perboli G, et al. In: Waste collection in urban areas: A case study. Vol. **48** Interfaces. 2018. p. 307–322

[16] Brotcorne L, Perboli G, Rosano M, et al. A managerial analysis of urban parcel delivery: A lean business approach. Sustainability. 2019;**11**:3439

[17] Perboli G. Guest-or linking lean business and or. In: Workshop of the 28th European Conference on Operation Research. Poznan, Poland, 2016

[18] Perboli G. The guest initiative. 2017

[19] Perboli G, Musso S, Rosano M. Blockchain in logistics and supply chain: A lean approach for designing real-world use cases. IEEE Access. 2018;**6**:62018–62028

[20] Cantamessa M, Gatteschi V, Perboli G, et al. Startups' roads to failure. Sustainability. 2018;**10**:2346

[21] Osterwalder A, Pigneur Y. Business Model Generation: A Handbook for Visionaries, Game Changers, and Challengers Hoboken, NJ. John Wiley & Sons; 2010

[22] P CONCORDIAC. CONCORDIA project Web Site; 2020

[23] INCIT-EV Consortium: INCIT-EV project Web Site. 2021

[24] NOUS Consortium: NOUS project Web Site. 2023

[25] SINFONICA Consortium: SINFONICA project Web Site. 2023

[26] Institute of Communication and Computer Systems. Piraeus Container Terminal; Vodafone (Greece): KPIs to evaluate the benefits of 5G and AI-enabled services deployment on ports logistics operations. Zenodo. [Dataset]. 2024. DOI: 10.5281/zenodo.10204619