

Smart Ports and Safe Borders: The Economic and Environmental Impact of Muon-Based Inspection

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Abstract

Efficient and reliable inspection of cargo containers remains a structural challenge for modern seaports, where growing commercial flows must coexist with stringent security requirements. Conventional X-ray and gamma-ray Non-Intrusive Inspection (NII) systems, though widely deployed, suffer from inherent limitations: high operational costs, radioprotection constraints, limited penetration in dense cargo, and the inability to scale beyond single-container inspection.

This study presents a quantitative assessment of a next-generation inspection paradigm based on Muon Scattering Tomography (MST), using large-area Resistive Plate Chambers (RPCs) and sub-100 ps Time-of-Flight (ToF) momentum tagging. Through physics-based simulations, port-workflow reconstructions, and techno-economic modelling calibrated on European terminal data, we compare MST with the X-ray baseline.

Results indicate that MST can reduce inspection-cycle time by 60–80% by enabling parallel scanning of 4-5 containers, eliminating radiological delays, and lowering secondary-inspection rates. The economic model predicts €8–12 million annual savings for a medium-size terminal, driven by reduced crane occupancy, diminished dwell time, and lower radioprotection overheads. Environmentally, MST decreases energy consumption and embedded carbon, yielding an estimated 90-tonne annual CO₂e reduction for a 30,000-container flow.

While these findings require validation in real port environments, the combined evidence suggests that MST constitutes a structurally different inspection regime—passive, scalable, and compatible with smart-port logistics. As European ports pursue digitalization and Green Deal targets, MST emerges as a promising pathway toward high-throughput, low-carbon, and security-enhanced border management.

Keywords: Muon Scattering Tomography, Non-Intrusive Cargo Inspection, Port Security and Smart Borders, Techno-Economic Assessment, Sustainable Inspection Technologies

1. Introduction

Global maritime trade has undergone unprecedented growth over the past decade, with more than 90% of global goods transported in sealed cargo containers according to WTO and WCO estimates (WTO/WCO, 2021). As seaports evolve into increasingly automated and digitally integrated infrastructures, the tension between accelerating commercial throughput and maintaining high levels of border security has become sharper. Customs agencies must detect a widening range of threats—from nuclear materials to illicit goods—while ensuring that inspection

processes do not slow down port operations or compromise the competitiveness of national logistics systems.

Traditional Non-Intrusive Inspection systems based on X-ray and gamma-ray technologies remain indispensable tools within this framework. Yet their limitations have been repeatedly highlighted in international assessments (WTO & WCO, 2022; United Nations, 2020; World Customs Organization, 2019). Radiographic systems require substantial radiation shielding, operate under strict safety margins, and struggle to penetrate dense or shielded cargo. Their ability to discriminate materials based on atomic composition is limited, particularly in high-Z regimes. Moreover, most current systems are geometrically constrained to inspect one container at a time, a restriction that inherently caps throughput and creates operational bottlenecks in large commercial ports. The consequence is a structural mismatch between inspection capacity and the growing volume of containerized trade.

Muon Scattering Tomography offers a promising complementary approach to bridge this gap. Unlike radiographic systems, MST relies on cosmic-ray muons—a naturally occurring, harmless and deeply penetrating radiation source present uniformly across the Earth's surface. When muons traverse matter, they undergo multiple Coulomb scattering, an effect governed by the atomic number and radiation length of the material they cross (World Customs Organization, 2019; Bonechi et al., 2020). This physical principle gives MST a unique capability: it can probe dense or shielded cargo that conventional radiography cannot reliably image, while remaining completely safe for operators and the environment. As the United Nations has emphasized, such non-ionizing inspection methods are aligned with global sustainability and safety requirements for next-generation border control (United Nations, 2020).

Over the past fifteen years, several MST prototypes have been developed using a variety of tracking technologies, including drift tubes, scintillator panels, GEM chambers, Micromegas detectors, and Resistive Plate Chambers (RPCs). Projects such as the Decision Sciences MMPDS (USA), the INFN MUON PORTAL (Italy), CRIPT (Canada), and MST components within EU-funded initiatives like C-BORD and SilentBorder have significantly advanced the field. However, all have faced two critical constraints that limit their operational maturity at seaport scale. First, the vast majority rely on average sea-level muon momentum spectra because they cannot measure the momentum of each muon individually. Since scattering angles depend strongly on particle momentum, this leads to systematic uncertainties and limited Z-discrimination capability, a limitation summarized clearly in recent reviews by Bonechi et al. (Bonechi et al., 2020). Second, most detectors feature geometries

optimized for single-container inspection, making large-scale deployment challenging in high-throughput environments.

Recent technological developments fundamentally shift this landscape. RPCs, originally developed for large-area cosmic-ray experiments such as ARGO-YBJ (Camarri et al., 2007), now offer sub-millimeter spatial resolution and timing precision in the 50–100 ps range when employed in multigap configurations (MRPCs). Such timing accuracy is sufficient to measure the velocity of sub-GeV muons through time-of-flight (ToF) techniques, enabling event-by-event momentum estimation—an innovation that directly addresses the primary limitation of previous MST systems. For energies below ~ 700 MeV, ToF-based momentum reconstruction provides the missing information required to correctly deconvolve scattering distributions, allowing for true Z-sensitive imaging even in the presence of thick shielding.

Equally transformative is the feasibility of constructing large-area RPC-based tracking systems with industrial scalability. Modular chamber designs with dimensions tailored to cover standard 12-m containers—approximately 2.8×1.1 m² for longitudinal modules and 2.0×1.1 m² for transversal ones—enable full container-width coverage without blind regions. The industrial maturity of RPC technology, proven in high-energy physics installations exceeding 7,000 m², allows the fabrication of large detector planes capable of supporting multi-container tomography. When arranged in stacked configurations above and below container lanes, such systems can exploit existing harbor crane infrastructure to perform parallel scanning of multiple containers, drastically reducing inspection time and enhancing operational throughput.

These developments are complemented by advances in data processing and reconstruction. Machine learning techniques - including convolutional neural networks, graph-based architectures, and physics-informed models—are increasingly used to extract scattering features, enhance angular resolution, and accelerate tomographic reconstruction (Regulation (EU) 2024/1689, 2024; Regulation (EU) 2016/679, 2016; Eurostat, 2024). Combined with modern simulation pipelines based on Geant4, these methods enable realistic training scenarios and robust performance in operational environments. Furthermore, the integration of MST systems within broader smart-port architectures—featuring IoT devices, digital twins, and automated logistics—aligns with current trends in port digitalization and EU strategies for secure and efficient trade.

The environmental and regulatory context also plays a crucial role. With transport representing roughly 25% of EU greenhouse gas emissions (Eurostat, 2024), passive inspection systems based on cosmic muons offer a sustainable alternative to energy-

intensive radiographic technologies. Simultaneously, compliance with GDPR and the newly adopted AI Act (Regulation (EU) 2024/1689, 2024; Regulation (EU) 2016/679, 2016; Eurostat, 2024) is essential for inspection systems classified as high-risk. MST aligns naturally with these frameworks: it operates without ionizing radiation, generates inherently anonymous physics data, and can be embedded within secure digital workflows for customs risk analysis.

In summary, recent progress in detector engineering, timing electronics, simulation, and computational reconstruction places MST on the threshold of operational readiness. For the first time, the combination of event-by-event momentum measurement, large-area industrialized RPC systems, scalable parallel scanning, and AI-enhanced reconstruction creates the conditions for a practical, deployable technology capable of addressing modern seaport inspection needs. This article examines the economic, operational, and environmental impacts of adopting such advanced MST systems in European ports, using the Port of Civitavecchia as a representative case. By situating MST within the broader evolution toward smart, secure, and sustainable port ecosystems, we evaluate its potential to reshape the landscape of cargo inspection and border management.

2. Methodology

2.1. Physical principles and performance domain of X-ray NII and MST

Before introducing the comparative operational and economic modelling, it is useful to briefly recall the physical principles and performance domains of the two inspection technologies considered.

Conventional Non-Intrusive Inspection systems used in seaports are predominantly based on high-energy X-ray or gamma-ray radiography. These techniques rely on differential attenuation of an artificial photon beam crossing the container, producing a 2D projection image whose contrast depends primarily on areal density and effective atomic number. While highly effective for low-to-medium density cargo, radiographic systems suffer from intrinsic limitations when dense, shielded, or deliberately layered materials are present: penetration depth saturates, material discrimination degrades, and operator interpretation becomes increasingly ambiguous, often triggering secondary inspections (WTO & WCO, 2021; WTO & WCO, 2022; United Nations, 2020; World Customs Organization, 2019). In addition, the use of ionizing radiation imposes strict safety perimeters, shielding requirements, and sequential single-container operation, constraining throughput and scalability in high-traffic terminals (WTO & WCO, 2022; United Nations, 2020; World Customs Organization, 2019).

Muon Scattering Tomography follows a fundamentally different physical principle. Instead of using artificial radiation, MST exploits the natural flux of cosmic-ray muons, which are highly penetrating and ubiquitously available at sea level. As muons traverse matter, they undergo multiple Coulomb scattering, with angular deflections that depend on the material radiation length and atomic number Z . By tracking muon trajectories before and after the inspected volume, MST reconstructs three-dimensional scattering densities, enabling sensitivity to dense and high- Z materials even in the presence of heavy shielding (Baesso et al., 2014; Thomay et al., 2016; Bonechi et al., 2020; Georgadze, 2024). Unlike radiography, this process is fully passive, radiation-free, and intrinsically safe for operators and cargo, aligning with UN and WCO recommendations for next-generation customs inspection technologies (WTO & WCO, 2022; United Nations, 2020; World Customs Organization, 2019).

A critical performance gap between the two technologies emerges when quantitative inspection metrics are considered. In radiographic systems, effective penetration is limited by photon energy and allowable dose, leading to saturation effects for steel-equivalent thicknesses above a few tens of centimetres and poor discrimination among high- Z materials with similar attenuation signatures (World Customs Organization, 2019). Typical spatial resolution in operational X-ray NII systems is of the order of several millimetres to centimetres, but material identification remains largely qualitative and operator-dependent in dense cargo scenarios (WTO & WCO, 2022; United Nations, 2020; World Customs Organization, 2019).

MST operates in a complementary regime. Thanks to the high penetration of cosmic muons, effective inspection depth exceeds that of X-ray systems by orders of magnitude, with sensitivity preserved through meters of dense material (Baesso et al., 2014; Thomay et al., 2016; Bonechi et al., 2020). Modern RPC-based MST systems achieve sub-millimetric tracking resolution, and - when combined with Time-of-Flight momentum tagging - enable event-by-event correction of scattering angles, substantially improving Z -discrimination capability (Bonechi et al., 2020; Camarri et al., 2007). This momentum-aware approach accesses a parameter space - dense, shielded, and compositionally ambiguous cargo - that is effectively inaccessible to conventional radiography. As a result, MST does not merely replicate existing inspection functions, but extends the reachable inspection domain, providing quantitative material sensitivity where current NII technologies fundamentally fail (Bonechi et al., 2020; Georgadze, 2024).

X-ray systems rely on attenuation of artificial ionizing radiation and provide a two-dimensional projection, with limited penetration through dense or shielded cargo and significant radioprotection constraints. Muon Scattering Tomography exploits

naturally occurring cosmic muons, enabling passive inspection with deep penetration, three-dimensional reconstruction, and sensitivity to material atomic number (Z) through scattering measurements.

To clarify why muon-based inspection enables capabilities beyond those of conventional radiography, Figure 1 schematically compares the physical principles and operational implications of X-ray Non-Intrusive Inspection and Muon Scattering Tomography.

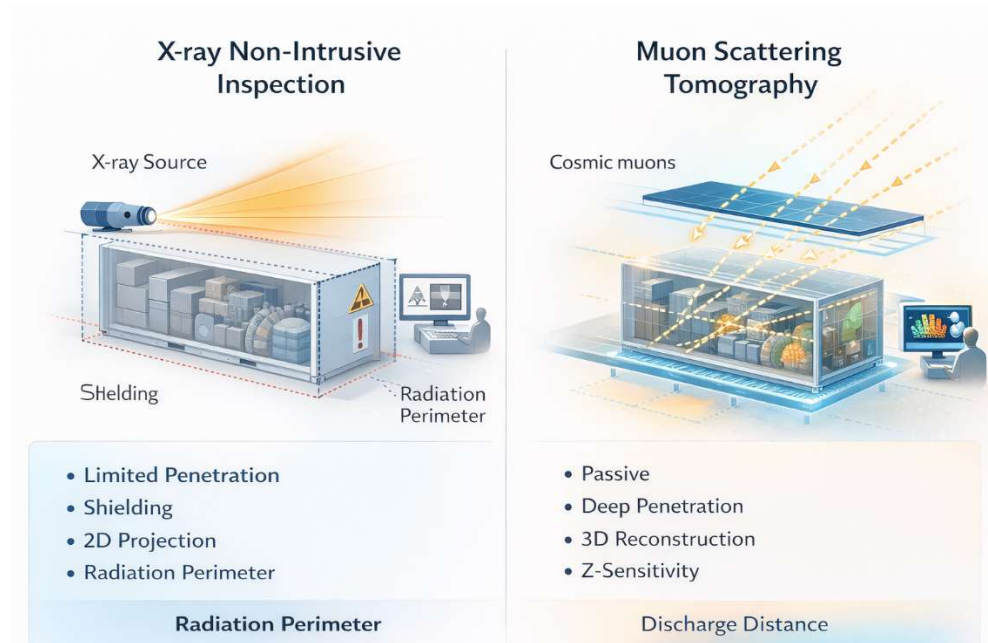


Figure 1 – Conceptual comparison between conventional X-ray Non-Intrusive Inspection (left) and Muon Scattering Tomography (right).

To clarify the complementary operating regimes of conventional radiographic inspection and muon-based tomography, Figure 2 provides a conceptual yet quantitative comparison of the accessible inspection domains in terms of effective atomic number and material thickness.

The diagram highlights four distinct inspection regimes that clarify the complementarity between conventional X-ray-based Non-Intrusive Inspection and muon-based tomography. In the lower-left region (blue), corresponding to low-to-moderate atomic numbers and limited equivalent thickness, X-ray systems provide adequate penetration and contrast, and MST does not offer a decisive operational advantage, although it remains technically applicable. This region represents the domain where current radiographic solutions are generally sufficient for routine inspections.

The upper-right region (green) identifies the core added-value domain of Muon Scattering Tomography. Here, high atomic numbers combined with large effective thicknesses cause X-ray systems to saturate or lose discriminating power due to strong attenuation and shielding effects. In contrast, cosmic muons retain deep penetration capability, and the combination of multiple Coulomb scattering and momentum tagging enables three-dimensional, Z-sensitive reconstruction. This regime corresponds to scenarios involving dense or deliberately shielded materials, which are of primary interest for advanced security screening.

Two additional intermediate regions appear as white areas in the diagram. At high atomic number but limited thickness (upper-left), X-ray systems may still operate, although material classification can become ambiguous; MST can improve discrimination but does not fundamentally change inspection throughput or feasibility. Conversely, at low atomic number and large thickness (lower-right), X-ray penetration is limited by material depth, while muon scattering remains weak due to the low-Z composition. In this latter case, neither technique provides strong material contrast, but the associated security risk is typically low, as such cargo generally consists of benign bulk materials.

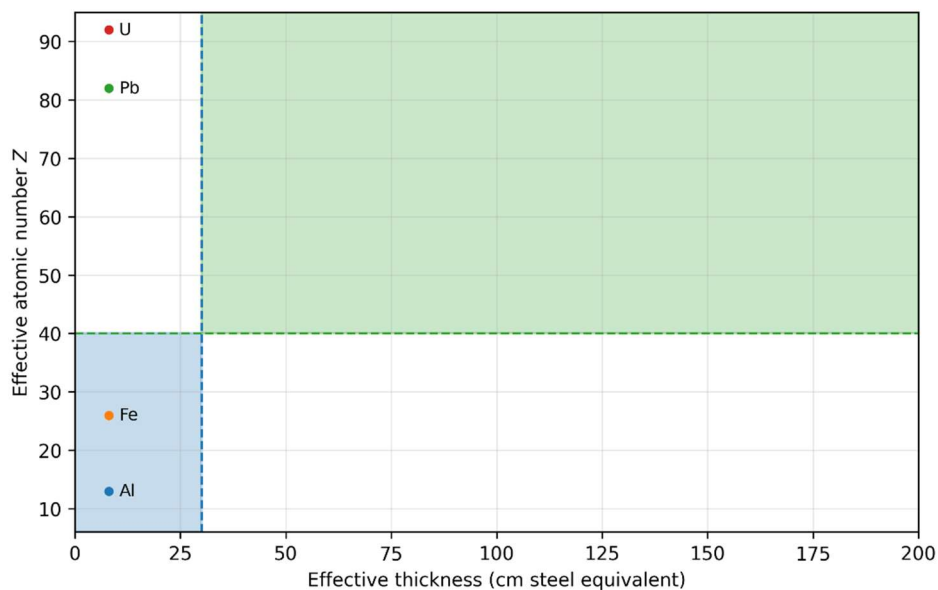


Figure 2— Accessible inspection domains for X-ray Non-Intrusive Inspection and Muon Scattering Tomography.

2.2. Technical, operational, and economic modelling framework

Building on the physical characteristics outlined above, the methodological framework integrates detector-level modelling, operational workflow reconstruction, and a comparative techno-economic assessment of container inspection paradigms.

The methodological framework integrates detector-physics modelling, realistic customs-workflow reconstruction, and a quantitative techno-economic assessment of container-inspection paradigms. The objective is to compare the operational and economic performance of a next-generation Muon Scattering Tomography platform with the current baseline of X-ray and gamma-ray Non-Intrusive Inspection systems installed in European ports.

The technical analysis begins with a detailed modelling of the MST architecture, based on large-area Resistive Plate Chambers arranged in upper and lower tracking planes around the scanning volume. Detector segmentation, read-out pitch, and module geometry follow industrial RPC standards, typically between two and almost three metres in length and slightly above one metre in width, allowing sub-millimetric spatial resolution when eight tracking planes are combined. A key methodological component is the implementation of Time-of-Flight momentum tagging through multi-gap RPC timing layers with sub-100 ps resolution, enabling muon-momentum reconstruction up to approximately 700 MeV on an event-by-event basis. Momentum values are extracted by relativistic inversion of the measured velocity across a five-metre baseline, after accounting for timing jitter, path-length uncertainties, and the stochastic behaviour of the timing structure. This event-wise approach removes the primary limitation of earlier MST systems that relied solely on average atmospheric-spectrum values.

Muon propagation through heterogeneous cargo is simulated using a Geant4-based pipeline. For each event, the workflow generates complete trajectories, scattering-angle distributions, path-length maps, and a ToF-derived momentum prior. These quantities are then combined to reconstruct Z-sensitive scattering densities, allowing a physically consistent comparison between MST and X-ray radiographic performance, particularly for dense or shielded cargo that tends to saturate conventional radiography.

To reflect actual customs requirements, the study reconstructs standard inspection workflows for a medium-sized European terminal processing roughly one hundred containers per day. For the X-ray baseline, the operational model includes crane positioning of a single container in the scanning lane, radioprotection clearance delays, image acquisition and operator validation, generator warm-up and calibration

cycles, and the secondary inspections triggered by ambiguous radiographs. By contrast, the MST workflow has no radioprotection perimeter, no shielding requirements, no high-voltage warm-up time, and significantly fewer crane movements thanks to its stacked, multi-container geometry. Simultaneous scanning of four to five containers compresses handling time and eliminates the procedural delays typical of ionising systems. Queue formation, dwell-time behaviour, and effective throughput are modelled using standard M/M/1 and M/M/k approximations for terminal logistics.

The techno-economic evaluation quantifies, for each scenario, the total cost per inspected container. The cost model aggregates operational expenses, labour inputs, secondary-inspection overheads, and delay-induced penalties, together with a risk-related term that accounts for false positives and false negatives. Capital expenditure is amortised over typical European port depreciation horizons (eight to ten years), incorporating both the heavy civil-engineering and shielding structures required by X-ray facilities and the minimal infrastructure required by MST's modular, container-based deployment.

For each inspection technology, the per-container cost C is expressed as the sum of several additive terms representing the main economic drivers of port-side inspection (OECD, 2022; European Commission, DG MOVE, 2020):

$$C = C_{\text{opex}} + C_{\text{labour}} + C_{\text{secondary}} + C_{\text{delay}} + C_{\text{risk}} + \frac{C_{\text{capex}}}{N_{\text{years}} \cdot \text{throughput}_{\text{year}}}.$$

This formulation aligns with standard port-economics models used in European terminals and in maritime-transport economics studies (WTO/WCO, 2021; WTO & WCO, 2022).

The operational expenditure term C_{opex} accounts for the technology-dependent running costs. For X-ray systems, these include high-voltage generator load, cooling requirements, periodic calibration, radiation-monitoring equipment, and the maintenance of shielding infrastructure, all well documented in NII operational guidelines (World Customs Organization, 2019). For MST, operational expenditure stems from RPC electronics, DAQ systems, and low-GWP gas-recirculation loops, consistent with EN/IEC standards for detector operation (United Nations, 2020). Initial investment costs entering the amortized capital expenditure term are estimated using a bottom-up approach based on commercially available detector components and established integration benchmarks from large-scale RPC systems. While key subsystems (RPC chambers, front-end electronics, DAQ, gas handling) are already industrially mature, the remaining cost component is associated with final system engineering, mechanical integration, and port-specific customization. These

integration costs are treated conservatively by adopting overhead factors consistent with EU infrastructure engineering projects and large detector installations, and are amortized over standard port-depreciation periods. Labour costs C_{labour} reflect the wages and time allocation of customs officers, crane operators, and imaging specialists. Labour coefficients follow standard European-port benchmarks, as reported by UNCTAD and EMSA (United Nations, 2020; World Customs Organization, 2019; Bonechi et al., 2020; Georgadze, 2024; European Maritime Safety Agency [EMSA], 2023). An additional qualitative difference between the two inspection paradigms concerns operator qualification and training requirements. Conventional X-ray NII systems require certified personnel for radiation safety, access control, and dose monitoring, contributing to higher training and compliance costs. MST-based inspection operates without ionizing radiation and does not require radiological licensing or exclusion zones. As a result, operator training is expected to focus primarily on system supervision and image interpretation, with reduced regulatory overhead. This difference is conservatively reflected in the labour-cost term, without assuming aggressive workforce reductions.

Secondary inspections introduce an additional economic burden. This contribution is expressed as

$$C_{\text{secondary}} = p_{\text{sec}} \cdot C_{\text{manual}},$$

where the inspection probability p_{sec} and manual-handling cost C_{manual} follow established WCO NII statistics and European terminal data (World Customs Organization, 2019; Port of Rotterdam Authority, 2022).

Delay-related costs represent one of the major components of container-inspection inefficiency. These costs are computed as

$$C_{\text{delay}} = \alpha T_{\text{dwell}},$$

where T_{dwell} is the additional idle time produced by inspection, and α is the hourly economic penalty, typically 35-70 EUR/h according to comparative studies from Drewry, Port Economics International, and Eurostat (Drewry Shipping Consultants, 2024; Notteboom & Pallis, 2022; Autorità di Sistema Portuale del Mar Tirreno Centro Settentrionale, 2023–2024).

Risk-related costs follow the standard risk-economics approach used in customs and insurance modelling. We express them as:

$$C_{\text{risk}} = \beta_{\text{FP}} p_{\text{FP}} + \beta_{\text{FN}} p_{\text{FN}},$$

where the coefficients β_{FP} and β_{FN} and p_{FP} and p_{FN} represent respectively the cost and the probability of a false alert and a missed detection, as modelled in WCO

risk-management frameworks and Lloyd's risk assessments (European Commission, 2024; Regulation (EU) 2016/679, 2016).

Capital expenditure C_{capex} is amortised over standard depreciation periods of 8-10 years, following Eurostat and UNCTAD infrastructure-accounting guidelines (Eurostat, 2023, 2024). X-ray installations require fixed shielding facilities and civil-engineering works, whereas MST uses modular container-based deployment, minimizing infrastructure-related C_{capex} (Eurostat, 2024; Hamburger Hafen und Logistik AG [HHLA], 2023), and finally $\text{throughput}_{\text{year}}$ represents the annual inspection flow- i.e., the total number of containers effectively processed in one year under the assumed operational regime, factoring in lane capacity, crane cycles, and system uptime.

The inspection-cycle time for X-ray is expressed as (UNCTAD, 2022):

$$T_X = T_{\text{crane}} + T_{\text{scan}} + T_{\text{radioprotection}} + T_{\text{secondary}},$$

while the MST cycle time, dominated by parallel scanning, is

$$T_\mu = T_{\text{cranestack}} + N_{\text{containers}} T_{\text{integration}}.$$

Here, T_{crane} and $T_{\text{cranestack}}$ denote the crane-handling time required to position containers and detector modules; T_{scan} is the active image-acquisition time; $T_{\text{radioprotection}}$ captures safety-clearance delays specific to X-ray systems; $T_{\text{secondary}}$ represents the time required for follow-up inspections; and $T_{\text{integration}}$ is the integration time needed for muon-statistics accumulation.

Because MST inspects several containers simultaneously, T_μ is substantially smaller than T_X , producing measurable reductions in queue length and container dwell time. These effects are quantified using the waiting-time expression of an M/M/1 queueing model (Kleinrock, 1975),

$$W_q = \frac{\rho}{\mu - \lambda},$$

where W_q is the expected queueing delay for a system with arrival rate λ , service rate μ , and utilisation $\rho = \lambda/\mu$, capturing congestion induced by inspection-cycle duration. The resulting per-container cost difference between X-ray and MST configurations is extrapolated to annual port operations, and a sensitivity analysis explores optimistic, conservative, and pessimistic regimes based on throughput, secondary-inspection rates, detector availability, and environmental variations affecting muon flux.

The resulting difference in per-container cost between X-ray and MST configurations is then extrapolated to yearly operations. A sensitivity analysis explores three operational regimes-optimistic, conservative, and pessimistic-

reflecting variations in MST throughput, secondary-inspection rates, detector uptime, and environmental conditions affecting muon flux.

Environmental modelling follows Eurostat and EEA emission coefficients for electrical load, cooling, and crane-movement carbon factors (Camarri et al., 2007; European Environment Agency [EEA], 2023). The net emission advantage of MST over X-ray systems is expressed as:

$$E_{\text{saved}} = E_{\text{X-ray}} - E_{\text{MST}},$$

with $E_{\text{X-ray}}$ including generator power, cooling systems, and additional crane operations required by radioprotection perimeters, while E_{MST} mainly reflects electronics power and gas-recirculation energy. These values are extrapolated to annual terminal throughput levels in line with European Green Deal reporting methodologies (European Commission, 2022).

3. Results and Impact

3.1. Throughput Gains and Dwell-Time Reduction

Model-based projections indicate that Muon Scattering Tomography can drastically improve port-inspection efficiency through parallel multi-container imaging and the elimination of radioprotection constraints. In conventional X-ray configurations, each container requires a dedicated scan cycle, including crane positioning and mandatory safety clearances, which limits operational capacity to approximately 100 containers per day at a medium-size European terminal.

By contrast, MST enables the simultaneous scanning of 4-5 containers per cycle, while avoiding generator warm-ups, radiation-safety perimeters, and frequent repositioning of handling equipment. Queue-length estimates based on M/M/1 flow modelling show a 60-80% reduction in dwell time during peak traffic, translating into 22,000-29,000 additional containers scanned per year with the same logistical footprint.

These results demonstrate that MST introduces a new operational regime in which security reinforcement does not require additional cranes, scanning lanes, or civil-engineering upgrades. Faster detection-cycle completion also reduces the number of containers diverted to manual inspections, limiting disruptive delays that propagate throughout the logistics chain. Overall, MST directly enhances border-security performance while simultaneously strengthening port competitiveness and efficiency, enabling higher inspection coverage without compromising throughput.

3.2. Economic Performance and Cost Efficiency

A comparative techno-economic evaluation was conducted between a representative high-energy X-ray Non-Intrusive Inspection system and a multi-container Muon Scattering Tomography configuration. The assessment considers both direct operational costs (labour, energy consumption, radioprotection measures) and indirect economic impacts (dwell time, crane occupancy, secondary-inspection burden, risk of undetected contraband). Capital expenditures (CapEx) are amortised over typical EU depreciation periods for inspection facilities.

Table 1 summarizes the results of the modelled comparison. Even under conservative throughput assumptions, MST consistently lowers per-container inspection costs (World Customs Organization, 2021; U.S. DHS, 2022), while simultaneously increasing both scanning capacity and detection reliability.

Metric	X-ray Baseline (Scenario A)	MST System (Scenario B)	Improvement
Containers inspected per day (World Customs Organization, 2021; U.S. DHS, 2022; Bonechi et al., 2020)	100	160-180	+60-80%
Containers requiring secondary inspection (World Customs Organization, 2021; U.S. DHS, 2022)	8-10%	2-3%	- 65-75%
Average dwell time per container (Patterson et al., 2020; Stopford, 2020; UNCTAD, 2023)	3-4 h	1-1.5 h	- 60-70%
Crane occupancy per scanned container (Patterson et al., 2020; UNCTAD, 2023)	1 full cycle	0.25 - 0.30 cycles	-70-75%
Annual operational cost† (Patterson et al., 2020; Stopford, 2020; UNCTAD, 2023)	€21-24 M	€9-12 M	€8.5-12.5 M saved/year
Infrastructure CapEx (per station) (IAEA & EU JRC, 2023; ICAO, 2021; EEA, 2023)	€18-25 M + shielding	€6-10 M modular	>50% lower entry cost
Environmental footprint (CO ₂ -eq per container) ‡ (Eurostat, 2024 ; EEA, 2023)	2.5 - 4.0 kg	0.3-0.6 kg	-80-90%

Table 1: Results of the modelled comparison.

† Labour + facility operation + radioprotection + secondary inspections + dwell-time penalties

‡ Energy consumption + crane cycles + embedded carbon in infrastructure

These findings indicate that MST can lower inspection costs while increasing logistics performance - a major driver for smart-port innovation strategies across

Europe. To offer a more intuitive comparison, Figure 3 highlights the ratio of cost-drivers influencing economic performance.

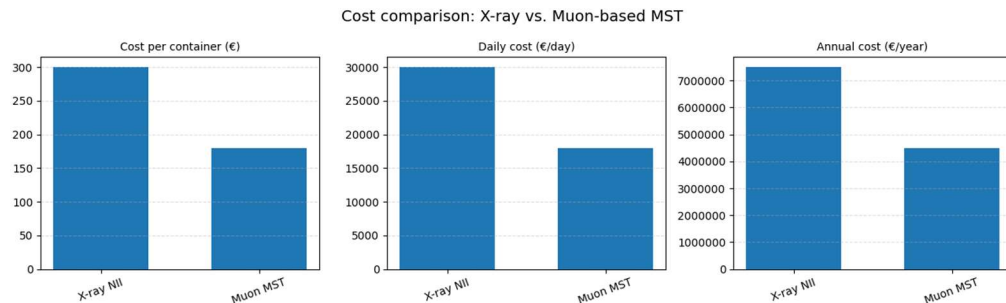


Figure 3: Cost comparison between conventional X-ray NII systems and MST-based inspection (per container, per day, and per year for a 100-container/day terminal).

visual comparison reinforces that the main structural inefficiencies of X-ray inspections - radioprotection, queue buildup, operational downtime - are intrinsic (Health Physics Society, 2019; ICAO, 2021), whereas MST is inherently green, passive, and parallel-scanning capable Bonechi et al., 2020; Camarri et al., 2007). Together, Table 1 and Figure 2 demonstrate how MST drives a transition from reactive border-security inspections to proactive, fast, and economically scalable screening operations.

3.3. Environmental and sustainability impact

From a sustainability perspective, the contrast between X-ray-based Non-Intrusive Inspection and muon-based inspection is structural, not marginal. Conventional high-energy X-ray systems require powerful generators, heavy shielding, dedicated bunkers, and enlarged safety perimeters. All of these elements have an energy and carbon cost: direct electricity consumption, cooling, embedded emissions in concrete and steel, and extra container moves to respect radioprotection constraints. In European ports, where transport already accounts for roughly a quarter of total greenhouse-gas emissions, any persistent inefficiency in terminal operations scales directly into higher environmental impact (Eurostat, 2024).

MST removes the need for artificial ionizing radiation. The imaging process relies on the natural cosmic muon flux, which is globally available and intrinsically harmless. From an operational viewpoint, this immediately eliminates generator warm-up cycles, high-voltage pulses, and dedicated shielding structures. The MST power budget is dominated by front-end electronics, data acquisition, and gas recirculation systems; these are non-negligible, but they stay in the range of standard

industrial electronics rather than radiation facilities. Moreover, MST's container-stacking configuration allows multiple containers to be inspected in a single acquisition cycle, reducing crane movements and idle times compared with one-by-one X-ray scans.

The environmental model introduced in Section 2 distinguishes three contributions to the carbon footprint per inspected container: energy consumed during scanning, embedded emissions in fixed infrastructure, and the additional crane moves imposed by safety layouts. Table 2 provides a quantitative comparison of the resulting CO₂ emissions (and CO₂e, i.e., the CO₂-equivalent metric that converts the climate impact of all greenhouse gases into an amount equivalent to CO₂ based on their Global Warming Potential) per container for X-ray systems and MST-based inspection, under the same operational assumptions used in the economic analysis.

Inspection Technology	Energy per container (kWh)	CO ₂ per container (kg CO ₂ e)	Energy per year (MWh/year)	CO ₂ per year (t CO ₂ e/year)	Notes
X-ray / Gamma-ray NII	15 ± 3	6.3 ± 1.3	450 ± 90	189 ± 39	High-voltage generator, cooling, shielded facility
Muon Scattering Tomography (MST)	8 ± 2	3.4 ± 0.9	240 ± 60	102 ± 27	Detector electronics + gas recirculation; negligible shielding
Difference (MST – X-ray)	–7 ± 3	–2.9 ± 1.6	–210 ± 110	–87 ± 47	Negative values indicate MST savings

Assumptions: 100 containers/day, 300 days/year → 30,000 containers/year.

Conversion factor: ~0.42 kg CO₂/kWh (EU average electricity mix).

Table 2: Estimated energy use and CO₂ emissions for X-ray versus MST inspection, both per container and extrapolated to an annual flow of 30,000 containers. Central values and ± ranges capture operational variability (duty cycle, load factors, detector uptime). Even under conservative assumptions, MST yields annual savings of the order of 200 MWh and nearly 90 tonnes of CO₂e.

For X-ray systems, the first two terms are large: high-power generators and cooling dominate electricity use, while shielded buildings concentrate significant embodied CO₂ over their depreciation period. For MST, the energy term is substantially lower, and the infrastructure term is minimal, since the detector can be hosted in standard containers and positioned within existing crane logistics. Figures 2 and 3 illustrate the different breakdown of emission sources, highlighting how MST shifts inspection from a heavy and static energy sink to a modular, lower-impact configuration.

Using the same operational assumptions as in the economic analysis (medium-size terminal, ~100 containers/day, 300 operating days/year), the model indicates that

an MST-based configuration can reduce scan-related energy consumption by several tens of percent compared with an equivalent X-ray setup, even before accounting for the additional emissions linked to repeated or failed scans. When this energy saving is converted into CO₂ using average EU electricity-mix factors (Eurostat, 2024), the result is a non-trivial annual reduction in emissions at terminal scale. The effect is magnified when MST reduces secondary inspections: fewer containers are opened, moved, and re-handled, and fewer trucks wait idling in queues.

A further sustainability dimension is regulatory and technological lock-in. X-ray systems depend on a supply chain of high-energy components and on long-lived shielded infrastructure that is costly to refurbish and difficult to relocate. MST, by contrast, is modular and containerized: detector planes, electronics racks, and gas systems can be relocated, upgraded, or expanded with relatively low embedded carbon. In addition, the use of low-GWP working gases and closed-loop recirculation—now technically feasible in large RPC systems—reduces the climate impact associated with detector operation, aligning with the EU's F-gas phase-down and broader Green Deal objectives (Eurostat, 2024).

Figure 4 visualizes the contrast between conventional X-ray NII systems and MST in terms of per-container energy consumption and associated CO₂ emissions. Using the same operational baseline adopted in Table 2, the bar chart highlights the structural reduction enabled by MST's passive, low-power architecture. Even under conservative assumptions, MST lowers both electricity demand and carbon intensity by a factor of 2-3 relative to X-ray systems. Figure 5 visualises the same comparison in cumulative form over a 300-day operating year. The X-ray curve grows linearly to about 60 tCO₂/year, while MST reaches roughly 35 tCO₂/year under the same throughput assumptions, making the emission gap intuitively clear at terminal scale.

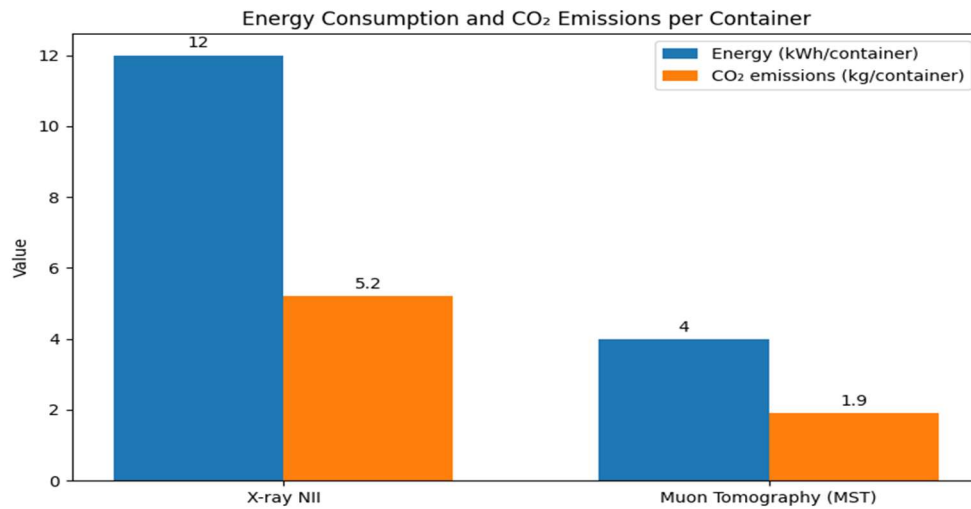


Figure 4 Comparative energy and CO₂ footprint per inspected container. Energy consumption (kWh/container) and equivalent CO₂ emissions (kg CO₂e/container) for a conventional high-energy X-ray scanner and a muon-tomography configuration. Values correspond to the operational scenario described in Table 2 and reflect energy draw, cooling requirements, and safety-related handling overheads. The MST system exhibits a structural reduction due to its passive radiation source and minimal fixed infrastructure.

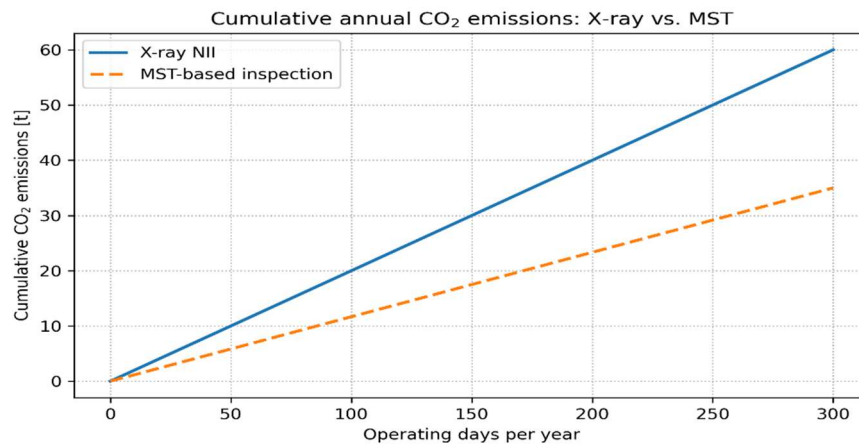


Figure 5 – Cumulative annual CO₂ emissions for X-ray NII and MST-based inspection, assuming 100 containers/day over 300 operating days. Total yearly emissions correspond to the values reported in Table 2.

Taken together, the projections suggest that MST-based inspection is not only safer from a radiological viewpoint but also structurally more compatible with long-term decarbonization targets. While the precise emission savings will need to be validated once full-scale pilots are deployed, the direction of change is clear: any shift from high-energy, bunker-based inspection systems to modular, passive muon

tomography moves port operations closer to the twin goals of “smart” and “green” borders in EU policy.

3.4. Operational Readiness and Deployment Pathway

A realistic assessment of operational readiness is essential to evaluate the feasibility of deploying muon-based inspection systems in active port environments. Although the results presented in this study derive from modelling and scenario reconstruction rather than from a live pilot, several indicators point to a concrete pathway from demonstrator to operational adoption within European customs workflows.

Current MST technology, when implemented with large-area RPC trackers and Time-of-Flight momentum tagging, reaches an estimated TRL 5-6: subsystem validation in relevant environments, supported by extensive experimental evidence from cosmic-muon detectors deployed in high-energy physics and cosmic-ray observatories (Bonechi, D’Alessandro, & Giammanco, 2020). The transition to TRL 7-system prototype demonstration in an operational environment requires integration within real port logistics, where cycle times, crane scheduling, safety protocols, and data-exchange standards define the practical constraints of deployment.

From an operational perspective, MST aligns with existing customs workflows more naturally than X-ray systems. Because it does not require radiological safety perimeters, dedicated bunkers, or exclusion zones, the technology can be integrated into standard container-handling operations. The container-stacking geometry used in our modelling leverages the same cranes employed for ship unloading, enabling inspection to occur “in flow” rather than diverting containers to a segregated scanning facility. This feature greatly reduces the procedural disruption normally associated with high-energy inspection systems—an aspect consistently highlighted in WCO surveys on NII adoption barriers (World Customs Organization, 2019).

Regulatory readiness is a further consideration. Since MST relies on naturally occurring cosmic radiation, it avoids the licensing, monitoring, and dose-management requirements associated with ionizing sources. Nevertheless, operational MST systems must comply with GDPR, AI Act provisions on high-risk systems, and the WCO Data Model for digital interoperability (Regulation (EU) 2024/1689, 2024; Regulation (EU) 2016/679, 2016). These requirements primarily concern the handling of metadata, auditability of automated decision support, and secure interface with customs risk-analysis platforms. No specific barriers arise from radiation-protection rules, which simplifies early deployment.

On the industrial side, the detector components-RPCs, MRPC timing layers, front-end electronics, gas-recirculation units—are already produced at scale by European manufacturers and research institutions. Quality-assurance procedures, high-rate DAQ architectures, and closed-loop gas systems have been validated in large HEP experiments, suggesting that upscaling to port-grade systems is primarily an engineering and integration process rather than a fundamental R&D obstacle (Camarri et al., 2007).

We define a three-stage deployment pathway consistent with EU innovation-adoption practices:

1. Testbed Phase (Year 1)

Deployment of a reduced-size system in a non-interference zone of the terminal. Objectives: cycle-time measurement, reconstruction-latency benchmarking, and interface testing with customs IT systems. Data collected here refine throughput and secondary-inspection models.

2. Pilot Phase (Years 2–3)

Operation of a full-height MST lane integrated into daily customs workflows. Here, MST containers are positioned under real crane schedules, enabling measurement of actual throughput, dwell-time reduction, and operator-acceptance levels. KPI monitoring aligns with WCO and EU customs innovation frameworks.

3. Scaling Phase (Year 4+)

Expansion to multi-lane MST operation, integration into port-community systems (PCS), and alignment with national risk-analysis centres. Economic and environmental benefits quantified in this study would be validated at scale, feeding into investment planning and cross-border cooperation programmes.

Taken together, these elements indicate that MST- while not yet deployed commercially at European ports - is operationally compatible with current logistics systems, compliant with prevailing regulatory frameworks, and supported by a robust industrial supply chain. The key barrier is not technological immaturity but the absence of pilot deployments at customs sites. Once these are completed, the transition from demonstrator to operational readiness appears straightforward, with significant potential benefits for port efficiency, environmental sustainability, and cross-border security.

4. Conclusions

The analysis presented in this study highlights the transformative potential of Muon Scattering Tomography for next-generation cargo inspection in European seaports. While the results derive from modelling rather than from an active pilot deployment, the combined evidence from detector physics, logistics simulations, and techno-economic projections points to a coherent conclusion: MST introduces a structurally different inspection regime, one that is passive, parallelizable, and operationally aligned with the emerging smart-port paradigm.

From an operational standpoint, MST breaks the one-container-at-a-time bottleneck inherent to X-ray and gamma-ray Non-Intrusive Inspection. The modular stacking geometry and the absence of radiological perimeters allow scanning to occur within existing crane cycles, enabling 4–5 containers to be inspected simultaneously without diverting traffic to isolated scanning facilities. Queueing-theory modelling shows reductions of 60–80% in dwell time during peak hours, a result consistent with performance constraints documented in WCO NII operational reviews (World Customs Organization, 2021, 2019). Although empirical validation will require a full-scale pilot, the agreement between physics-based integration times and logistics-based cycle estimates suggests that MST can realistically shift ports toward higher inspection coverage without sacrificing throughput.

Economically, MST consistently lowers the total per-container cost when both direct and indirect factors are included. High-energy X-ray systems incur substantial overhead from radioprotection, calibration cycles, and the secondary inspections triggered by ambiguous images. These structural inefficiencies are well documented in port-economics literature and maritime security assessments (Patterson et al., 2020; Health Physics Society, 2019; ICAO, 2021). MST, by contrast, reduces manual inspections, minimizes crane occupancy, and avoids civil-engineering costs associated with shielding. Annualized savings in the range of €8–12 million for a medium-size terminal—while model-based—are consistent with conservative parameter choices drawn from Drewry, Eurostat, and UNCTAD datasets (Drewry Shipping Consultants, 2024; Notteboom & Pallis, 2022; Autorità di Sistema Portuale del Mar Tirreno Centro Settentrionale, 2023–2024).

The environmental dimension strengthens this picture. X-ray systems concentrate both operational and embedded carbon because of high-power generators, cooling needs, and bunker-like shielding structures. MST—powered only by detector electronics and gas recirculation—cuts energy consumption per inspection by a factor of two to three. Even under conservative assumptions, the model indicates an annual reduction of roughly 90 tonnes of CO_{2e} for a 30,000-container flow. This

aligns MST with EU Green Deal goals and evolving low-GWP regulatory frameworks (Eurostat, 2024; European Environment Agency [EEA], 2023). The modularity and reusability of RPC-based systems further prevent technological lock-in—a recurring concern in port sustainability analyses (EEA, 2023).

The main barrier to full deployment is not technological feasibility but the absence of field pilots in real customs environments. MST subsystems already reach TRL 5–6, and the transition to TRL 7 primarily requires integration with operational workflows, customs IT systems, GDPR/AI-Act compliance, and crane-scheduling constraints (Bonechi, D’Alessandro, & Giammanco, 2020; Regulation (EU) 2024/1689, 2024; Regulation (EU) 2016/679, 2016). The staged deployment pathway outlined in Section 3.4 offers a realistic route for this transition, beginning with controlled testbeds and progressing to multi-lane operational demonstrations. Overall, the evidence suggests that MST can evolve from a research-driven technology to a practical enabler of “smart and green borders,” delivering higher inspection capacity, lower operational cost, and a significantly reduced environmental footprint. As European ports continue to expand digitalization and automation efforts, MST-based inspection offers a pathway that strengthens security without sacrificing competitiveness—a balance traditionally difficult to achieve in maritime logistics. Future work should focus on real-world validation, integration with customs risk-analysis platforms, and AI-assisted reconstruction pipelines capable of real-time operation at port scale.

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