

RESILIENCE AND SUSTAINABILITY IMPACT ASSESSMENT FRAMEWORK FOR PORT QUAY WALLS

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Abstract

As critical nodes of global trade networks, ports are increasingly exposed to climate related hazards which threaten their operation. The Climate Resilient Port Infrastructure project (CLARION), funded by Horizon Europe, tackles this challenge through research in port infrastructure resilience across four major European ports. The focus of this paper is to present the impact assessment framework developed within the CLARION project, which presents itself as Key Performance Indicators (KPI), sorted in five major groups which are reliability, mobility & operational efficiency, economic performance, environmental performance and technical KPIs, and sorted in three different resilience phases, preparedness, response, recovery. CLARION project consists of 10 Pilot Demonstrators. In this paper the framework is applied to Pilot Demonstrator 1, Smart & sustainable climate resilient quay walls, performed at the Port of Rotterdam in the Netherlands. This analysis demonstrates that the integration of Digital Twin technologies and remote sensors have the potential to enable transition from assumption-based design to data driven condition assessment, which would improve structural reliability, reduce construction and maintenance costs while also lowering carbon footprint. Proposed framework effectively supports more informed maintenance planning, risk reduction long term sustainability and climate resilience of port infrastructure.

Key words

Port Infrastructure, Resilience, Impact Assessment, Quay wall, Key Performance Indicators

1. Introduction

With the increase of global trading, ports have become vital and critical nodes of the whole logistics system as they are an intersection of the maritime, rail and road networks where goods change mode of transport. As their location is fixed on the interface between land and sea, any disruption to their continuous operation can have significant impact on local and international trade chains. Climate change amplifies the intensity of natural hazards such as storms, floods, heat waves and hurricanes, which already affect ports worldwide. 90 % of ports worldwide face multiple climate related hazards which exposes €7.5 billion of infrastructure and €63.1 billion of trade to risk (Seatrade Maritime News, 2024).

Besides climate hazards, man-made hazards give additional layer of complexity to the port operations. The 2021 Suez Canal blockage demonstrated the fragility of global trade as a single operational incident cascaded and slowed the logistics throughout the world. Since ports represent multimodal intersections of logistical lines, a disruption in one location can create ripple effects that echo beyond a single country.

The CLARION (Climate Resilient Port Infrastructure) project, funded by Horizon Europe, aims to advance research in the field of port infrastructure resilience and its hinterland transport networks by enhancing operational safety, security and environmental sustainability. In the project, ten Pilot Demonstrations take place across four major European ports (Rotterdam, Antwerp-Bruges, Hamburg and Constanta) to implement and test new technological solutions.

This paper presents the resilience and sustainability impact assessment framework developed in the CLARION project, while also including the Key Performance Indicator (KPI) framework to evaluate and measure the impact of each pilot demonstrator. This framework is afterwards presented in the context of Pilot Demonstrator 1, Smart and sustainable Climate resilient quay walls at the port of Rotterdam, to demonstrate its practical applicability.

2. Methodology for impact assessment

2.1. Resilience & Sustainability concept

Currently, risk management in ports is primarily reactive in nature, as actions only take place once disruptions occur. Given the importance of ports in the global economy, a paradigm shift to a proactive approach to resilience is needed (Arup, 2022). In the context of ports, resilience can be broadly defined as the ability to maintain acceptable level of service despite disruptions. This means that resilience can be measured and described temporally as Time to Recovery, i.e. the amount of time needed for a port to resume its operations at an adequate capacity after it is affected by a disruption (UNCTAD, 2022b). Shorter Time to Recovery means that port is more resilient. This concept is illustrated in Figure through the resilience curve. It displays port operational capacity against time throughout the whole resilience lifecycle.

Preparedness represents all proactive measures taken before a disruption takes place, as it aims on reducing disruptions impact and enabling faster recovery. They can take the form of hazard identification, vulnerability assessment and mitigation investment. All of them strengthening a port to absorb the initial shock. Early Warning & Response consists of immediate actions once a disruption occurs. They aim to slow down the drop in operational capacity so that recovery phase can be shorter. Early warning actions take place in the preparedness phase, but their effects are only visible in the response phase. Recovery is all work performed to return capacity of port operations to normal levels. Effective recovery strategies minimize the effect on logistical network.

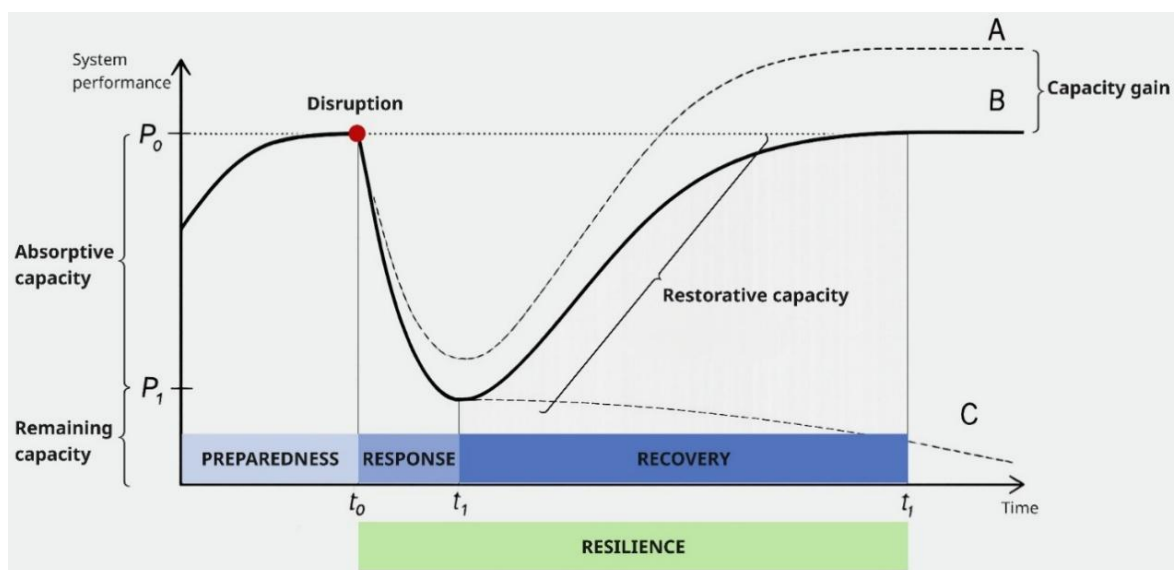


Figure 1 Resilience phases (adapted from Bruneau et. al., 2003; and Linkov & Palma-Oliveira 2017)

Together, these phases form a continuous cycle that all ports experience. Investments in preparedness phase aim to make recoveries faster during the response and recovery phases, while lessons learned in recovery phases feed back into preparedness and responses as new measures are taken to mitigate drop in operational capacity and procedures are adopted which dampen the drop in the response phase.

Pilot Demonstrations in CLARION take place in all resilience phases: Rotterdam PDs focus on Preparedness and Prevention where they tackle the challenge such as quay wall resilience, sediment reuse, nature-based solutions and hinterland transport resilience. Hamburg PDs focus on Response and Recovery through Flood impact control and extreme weather forecasting. Antwerp-Bruges PDs address both Preparedness and Response by covering corrosion monitoring of port infrastructure and shore tension management for Ro-Ro and Con-Ro terminals in hazardous weather conditions. Constanta Pilot Demonstration spans all phases through Federated learning for cadastral measurements and inland water level forecasting. Finally, Pilot Demonstration regarding Emergency Management System addresses all three phases of resilience.

Parallel to resilience, sustainability is equally significant variable of port infrastructure management. In the context of port infrastructure sustainability is defined as business strategies and activities that address the present and future needs of the port and its stakeholders, while safeguarding both human and natural resources (AAPA, 2007).

Resilience and sustainability are mutually reinforcing objectives, rather than competing ones. Infrastructure designed considering sustainability, optimising material use, reducing emissions and extending service life is more capable of absorbing and recovering from disruption. Proportionally, resilient infrastructure that maintains functionality under disruptions reduces the need for emergency measures, which in long term protects economic and environmental resources.

2.2. Resilience and sustainability impact assessment framework

In the CLARION project, an impact assessment framework is structured around sets of Key Performance Indicators (KPI) organized into five categories: Reliability, Mobility and Operational Efficiency, Economic Performance, Environmental Performance, and Technical. Each of these categories addresses a distinct dimension of port resilience and sustainability. Besides categorical mapping, KPIs are further mapped to the three resilience phases, to show not only when is the solution being utilized, but at what stage of the life cycle does it contribute the most.

The KPI Framework was developed through an iterative and collaborative process to establish suitability for each pilot demonstration. Development was done in four stages:

- (1) A literature review that covered relevant standards, published papers and previous EU projects such as CIRCUIT (Stipanovic et al. 2023), SAFE-10-T (de Paor & Connolly, 2017; Reale et al. 2017) and BEEYONDERS (Stipanovic et al. 2023)
- (2) Interactive online workshops with Pilot Demonstration representatives for verification of the initial KPI's
- (3) An in-person workshops held during the Plenary Meeting of the project at the Port of Hamburg for additional layer of input
- (4) Consolidation of all collected data and information

KPI Categories in the CLARION project are derived from objectives defined in Project Deliverables D2.1 (Roukouni, A. & Kanellopoulos, G, 2025a) and D3.1. (Roukouni, A. & Kanellopoulos, G, 2025b). Starting four categories were expanded during the workshop phase to five by including a technical category, which covers topics such as digital and analytical tools which are at the core of the project innovations.

2.3. Key Performance Categories

Reliability refers to the property of system to perform its function for a specified period under defined operating conditions. It quantifies port resilience by focusing on maintenance of functionality in case of ports, it refers to the functionality of critical assets such as quay walls, mooring systems and breakwaters under stress conditions. It is structured around two complementary aspects of reliability, Capacity and Loads. Capacity is the ability of the system to resist external loading on the system, and loads represent the exterior stresses that impact the system, such as environmental hazards, operational and accidental actions. Failure of the system occurs when the loading exceeds available capacity. On the resilience curve, Reliability KPIs primarily contribute to the Preparedness & Prevention phase. KPIs within the framework are developed in alignment with ISO 2394:2015 for probabilistic reliability assessment, EN 1990 for structural design, EN 1997 for geotechnical aspects, and ISO 13822:2010 for evaluation of existing structures

While the Reliability KPIs focus on physical resistance of the port system, *Mobility & Operational Efficiency* (M&OE) covers the response and recovery performance of ports as they are a measurement of how fast and efficiently can port operations adapt to hazardous conditions and recover to status before hazard. Some of the tools that Mobility & Operational Efficiency KPIs assess are forecasting, smart management and multimodal operability. Category is organized into three subcategories. Operability subcategory focuses on the agility of port systems intended to restore operations once a disruption occurs. Forecasting & Decision-making subcategory covers the efficiency of monitoring and utilizing available information's to make data-driven decisions for the benefit of port operations under disruption. Final subcategory, Transport System Performance & Multimodality evaluates performance of hinterland network and multimodal aspect of transport in the event of disruptions blocking a certain mode. M&OE KPIs are primarily mapped to the response and recovery phases of the resilience lifecycle.

Financial dimension of port operations and its resource allocation is evaluated in the *Economic Performance* KPIs. It covers full infrastructure lifecycle, from design and construction, to operation, maintenance and recovery. Category is based on ISO 15686-5:2017 - Part 5: Life-cycle costing. It is additionally subdivided into three subcategories. Capital Expenditure (CAPEX) subcategory covers the construction cost per functional unit and enables comparison of conventional and CLARION design approaches. Operational Expenditure (OPEX) subcategory includes all recurring costs in the lifecycle of an infrastructure such as inspection, maintenance, monitoring, repair and reconstruction cost. Final subcategory, Total Lifecycle cost takes a holistic approach to all cost components and integrates them into a single measure that evaluates assets across whole lifespan. Economic performance spans all resilience phases and enables evaluation of resource allocation for long-term and short-term port management.

Environmental performance KPIs assess the environmental impacts throughout the full life cycle of infrastructure. Category covers both direct and indirect environmental impacts. They are aligned with EN 15804 and ISO 14044:2006. The KPIs are additionally subdivided into three subcategories. KPIs of the Life Cycle Assessment (LCA) subcategory quantify the environmental footprint of pilot demonstrators. Pollution subcategory encompasses impacts during extreme events such as debris protrusion and environmental compliance to regulatory thresholds. Final subcategory, Biodiversity covers the ecological dimension specific for Pilot Demonstrators that include nature-based solutions and therefore require water quality monitoring and biodiversity measure. Environmental performance KPIs span all resilience phases.

Technical KPIs evaluate tools and systems developed within CLARION, mainly their digital maturity and quality of data and how it transforms into actionable insights for port management. They are subdivided into three categories. Resilience-related subcategory covers KPIs that assess the use of digital data for furthering resilience of ports, such as repurpose of Digital Models. Operational Efficiency related subcategory KPIs assess the capability of tools to increase ports efficiency through digitalization, faster, data-driven action and more in-depth analysis post disruption. Final subcategory, Monitoring Data Quality, covers aspects of data and

how its quality improves decision-making. Technical KPIs cover all resilience phases and showcase how digital backbone enables situational awareness and evidence-based decision making.

3. KPI Framework application

3.1. Description of CLARION Pilot Demonstrator Smart & sustainable climate resilient quay walls

The Port of Rotterdam is one of Europe's largest ports, covering 125 km² of land and water combined, with more than 60 km² of industrial sites (Stipanović et al., 2024). One of the significant issues the port faces because of changing climate is temperature fluctuation, which induces cyclic thermal loading on quay wall structures. This causes repeated wall displacements that, over time, can approach the ultimate limits of serviceability, threatening structural integrity and operational continuity.

A baseline solution to which the CLARION solution is compared to is a quay wall structure before any optimization measures have been implemented. The structure in question is shown in Figure (Alver et al. 2026). It is a deep-sea quay wall with a retaining height of 29 m which spans 2.2 kilometres of coast. The primary soil retaining structure is provided by open-ended piles with diameter of 1.4 m, and they are spaced 3.3 m centre to centre. They are tied back with anchors that are driven into a sand layer. On top, a concrete relieving platform runs the full length of the structure. Throughout the whole structure, thousands of anchors and piles are installed which along with conservative design assumptions that can accumulate into significant material overuse (Duffy et.al, 2024).

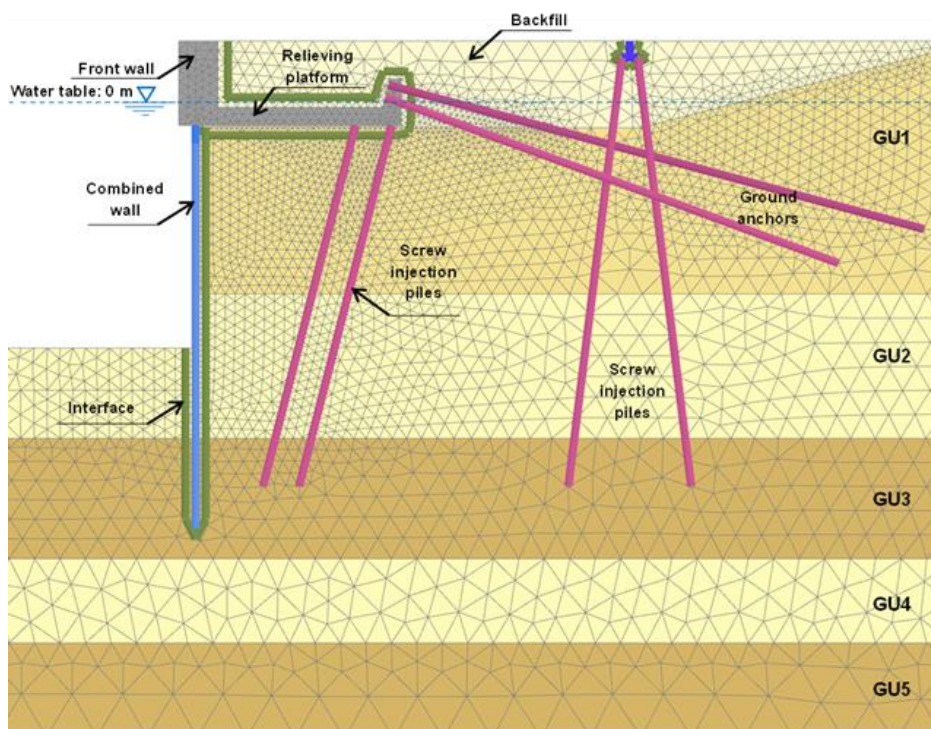


Figure 2 Numerical model of the Port of Rotterdam quay wall cross-section (Alver et al. 2026)

Building upon this baseline, PD1 introduces fibre optic sensors embedded directly into the quay wall elements during construction, enabling continuous monitoring of anchor forces, wall deformations and water pressure arising from environmental effects including temperature change. The sensor data is validated against a Plaxis 2D numerical model and integrated into a high-fidelity Digital Twin, creating a live connection between the physical structure and its digital representation. This results in a fundamental shift from conservative assumption-based design to condition-based management powered by real structural data. The Digital Twin enables predictive maintenance strategies that respond to actual infrastructure condition rather than fixed

inspection intervals or worst-case theoretical scenarios, with expected benefits across reliability, economic performance, environmental impact and digital maturity of the asset.

3.2. KPI Framework Applied to PD1

The KPI framework is shown in Figure . KPIs selected for quay wall pilot demonstrator show that it is a structural and digital innovation rather than an operational one, therefore the Mobility & Operational Efficiency KPIs are not applied. In this case the framework is focused on the physical performance and economic and environmental impacts. Technical aspect is also evaluated through the reusability of the Digital Twin.

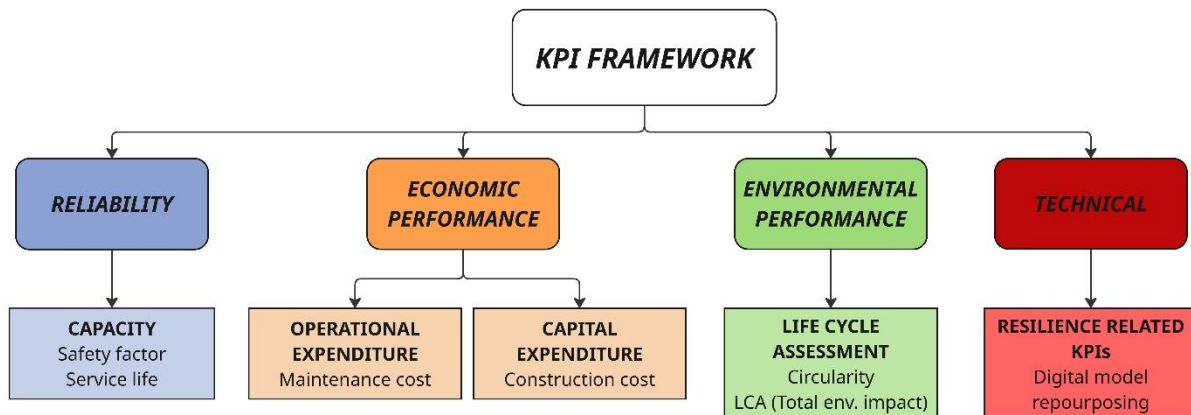


Figure 3 KPI framework for quay wall CLARION Pilot Demonstrator

Table presents KPIs developed within CLARION framework as they are applied to Pilot Demonstration 1 - Smart and sustainable Climate resilient quay walls along with their short description, unit and resilience phase.

Table 1 KPIs for Quay wall CLARION Pilot Demonstrator

Category	Indicator	Description	Unit	Resilience Phase
Reliability	Safety factor	Ratio of stabilizing to destabilizing forces	n	Preparedness & Prevention
	Service life	Expected asset service life	years	
Economic Performance	Maintenance cost	Annual maintenance cost per structural functional unit	€/FU·year	
	Construction cost	Construction cost per structural functional unit	€/FU	
Environmental Performance	Circularity	Percentage of material to be reused/recycled at end of life	%	Recovery
	LCA – Total env. impact	Life cycle assessment impact (scope and functional unit defined per PD)	kg CO _{2e} /FU	All phases
Technical	Digital model repurposing	Ability to repurpose DT for different load conditions/wall uses	Y/N	All phases

Considering all four categories on a time scale, KPIs are primarily mapped to the Preparedness & Prevention phase, consistent with this pilot demonstrator’s position on the resilience curve. The Digital Twin technology enabled by sensors allow for acting before the disruption occurs, making more accurate structural assessment, leaner design and predictive maintenance possible, which in turn strengthens port’s absorptive capacity.

For the evaluation of the quay wall pilot demonstrator the functional unit of 100m length of quay wall supporting the defined design load is established. Data requirements and quantification methods vary by KPIs. For Safety Factor relevant inputs are soil parameters, design drawings, material properties and environmental

conditions to compare safety factors for the limit equilibrium calculation utilizing identical model approach between baseline and CLARION solution. Service Life requires the same structural inputs, applying them to deterioration models on both scenarios. Maintenance Cost is based not only on the same design drawings, but also on maintenance strategies and reference prices to compare annual maintenance costs based on predefined inspection and intervention activities. Construction Cost requires Bill of Quantities and reference prices to compare total construction cost between conventional and optimised design. LCA – Total environmental impact also uses the bill of Quantities but from a different perspective – to quantify the carbon emissions and broader environmental benefits of material optimisation. Same goes for the circularity, which by adding material specifications assesses the recyclability or reusability of each structural component. Finally, Digital Model Repurposing is dependent on digital model availability, assessing if the Digital Twin developed for the quay wall can be adapted for different load conditions or repurposed for future engineering applications.

4. Conclusion

This paper presents the resilience and sustainability impact assessment framework developed in the CLARION project and demonstrated its application to Pilot Demonstrator for Smart and sustainable climate resilient quay walls at the Port of Rotterdam. The core contribution of the framework is the ability to map of the KPIs to phases of the resilience lifecycle which allows solutions to be evaluated what they achieve and when they impact port operations the most. Besides that, explicit integration of sustainability as a complementary dimension to resilience shows that more resilient infrastructure is inherently more sustainable, and vice versa. When applied to a quay walls, it could be expected that the deployment of sensors and Digital Twin technologies could be expected to extend the service life of quay wall infrastructure. This is consequential, not only in reliability terms, but across all framework categories as it simultaneously reduces lifecycle costs, emissions and material impact since longer operational period proportionally improves performance on all indicators. In the next phase of work we will use inputs to determine this impact.

The framework is not limited in the type of infrastructure it can assess. Primarily developed for all ten CLARION Pilot Demonstrators which span solutions impacting flood control, corrosion monitoring and hinterland transport resilience it can easily be reapplied to any new solutions wanting to improve resilience and sustainability of port and its operations no matter the type or scale of solution.

Finally, this work supports a broader argument relevant to investment decisions. Regardless of the funding level, be it institutional or European level, they would all benefit from holistic methodologies that are tailored to specific operational and environmental conditions of port logistics industry. Frameworks such as the one represented here provide multiple dimensions on which such decisions are required to be taken. That way, decisions will not be taken on singular criteria which often cannot consider the complexity of port logistics or optimise for its resilience.

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