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Vulnerability and Recovery Co-Analysis to Enhance Resilience of Ports Impacted By Extreme Weather Events - Preliminary Results from EU Project Safari

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Abstract **–** Ports play a critical role in global commerce, acting as vital nodes in the supply chain for goods and services. However, their strategic coastal locations make them particularly vulnerable to extreme weather events, intensified nowadays by climate change. In Europe, where ports are integral to economic stability and regional connectivity, the need for robust vulnerability analysis and resilience planning has become a pressing concern. This paper explores the first steps in the process of establishing the practical application of a combined framework for assessing port vulnerabilities and developing recovery plans to mitigate the impacts of extreme weather events on port operations. The study focuses on the European ports considered in the research project *Safe and Climate Resilient Ports (SAFARI*). The historical weather analysis shows that the *SAFARI* project ports are subject to an increasing risk of flooding and heatwaves. The definition of port functions, associated stakeholders and infrastructure together with their vulnerability to these events is conducted as a starting point to develop port recovery plans as part of port resilience capabilities

Keywords**:** Climate Change, Port Resilience, Safety, Port Recovery, Maritime Transport, Critical Infrastructure

1. Introduction

The increasing frequency and intensity of extreme weather events, driven by climate change, pose significant challenges to the operational resilience of ports in Europe. These ports, critical nodes in global supply chains, are highly vulnerable to disruptions such as storms, flooding, and heatwaves [1]. These disruptions lead to cascading economic consequences, with over 70% of European ports now adapting infrastructure to enhance resilience [2]. The need for an integrated approach to assess vulnerabilities and implement recovery strategies has been highlighted by stakeholders [3,4].

The vulnerability of ports to climate-induced disruptions encompasses three key components namely exposure, sensitivity, and adaptive capacity [5]. To effectively assess vulnerability, it is essential to understand the port´s exposure to extreme weather risks. Various studies have highlighted the increasing frequency of extreme weather events, such as tropical cyclones and sea-level rise, which pose significant threats to port infrastructure and operations [6,7] emphasizing the need for comprehensive risk assessments that account for both natural and anthropogenic factors [7]

Besides vulnerability analysis, recovery planning is a critical aspect of port resilience, as extreme weather events like floods and hurricanes can disrupt operations for extended periods, with floods causing an average disruption of 11 days [8]. Strategies must address both immediate and long-term vulnerabilities [9]. The development of a cohesive framework for vulnerability analysis and recovery planning involves synthesizing various methodologies and approaches. For instance, tools such as the indicator-Based Vulnerability Assessment (IBVA) help identify and rank vulnerable components [5].

Network analysis and stakeholder-informed frameworks further support effective planning by revealing interdependencies and aligning recovery actions with user expectations [10].

This paper aims to integrate vulnerability analysis and recovery planning into a cohesive framework tailored into the unique operational and environmental contexts of the pilot ports (Dunkirk, Seville, Lisbon) as understood within the context of the SAFARI project. The focus is on the enhancement of rapid recovery of port operations under extreme climate-induced disruptions in the pilot ports of Seville, Dunkirk, and Lisbon.

2. Methodology

The methodology adopted in this study combines existing frameworks in the literature aimed at enhancing port resilience to climate change [11,8,3]. It consists of two main steps: climate scenario projection and vulnerability classification, and port operations recovery planning. Figure 1 illustrates the first step, which involves analysing historical weather data and projecting future extreme weather scenarios. The climate models and variables used are adapted to the specific geographical regions of the SAFARI case study ports. Projected climate variables define short-, medium-, and long-term scenarios, each assigned a severity index based on anticipated impact. Port infrastructure is then categorized as critical or non-critical, supporting the recovery planning in the next step.

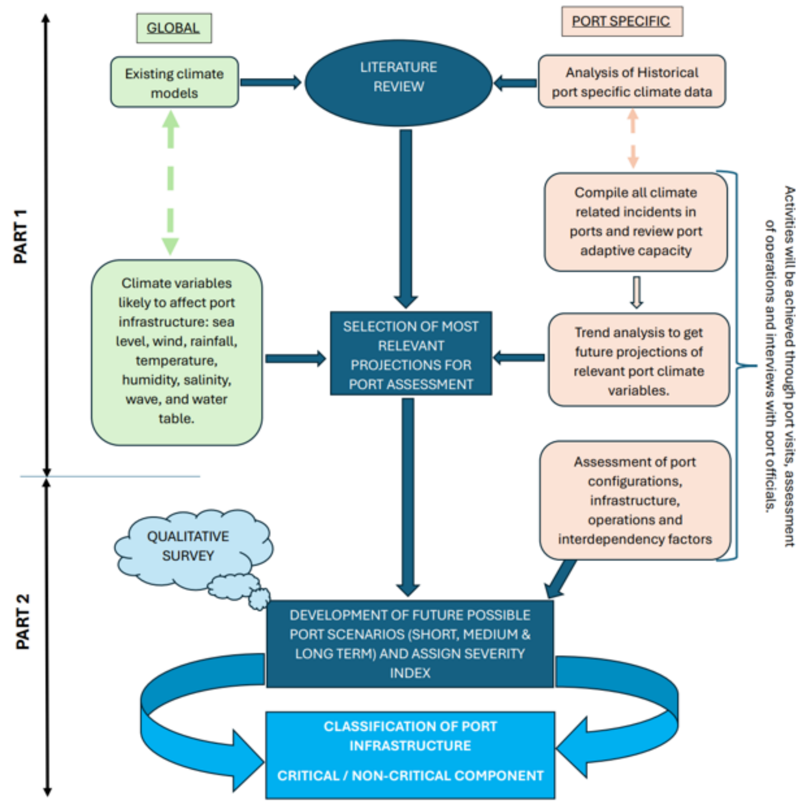

Figure 1: Climate scenario projection and vulnerability classification

Figure 2 outlines the recovery plan, which is based on understanding port components, their interconnections, and disruption levels. The goal is to maintain at least 80% operational capacity during extreme events through structured measures. The plan includes two layers: (i) the Incident Command Structure (ICS), responsible for managing responses, and (ii) Actions and Alternative Operations, which execute recovery tasks. Recovery actions are defined by function, initiator, implementation process, required resources, and execution timeline, based on climate risks, vulnerabilities, and interdependencies.

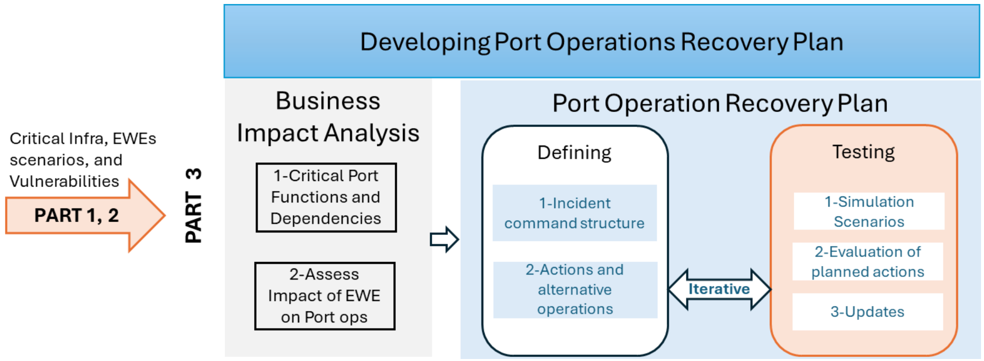

Figure 2: Developing port operations recovery plan

3. Initial Results and Discussion

The first part of the proposed framework was applied to the pilot ports of the SAFARI projects. Therefore, the analysis of the past extreme weather events in the port regions is presented in the following sub-sections (3.1 and 3.2). Additionally, part 3 of the framework is partially applied to map the main functions of a port container terminal.

3.1. Description of Ports and Main Climatic Characteristics

The Port of Seville is the inland port in Spain, located on the Guadalquivir River. It handles frequent small ship traffic and has a channel length of 80 km. The port is well connected via railway, airport, and motorway, emphasizing its role as an intermodal center [12]. A lock at the entrance protects it from tidal influences. The region has a Mediterranean climate with an average temperature of 18 °C [13]. Rainfall is 983 mm during wet months (Nov-Apr) and 260 mm during dry months (May-Oct), with up to half of annual rainfall occurring in 24 hours. This variability increases drought and flood risks [14].

Lisbon port is the third largest in Portugal, is situated where the Tagus River meets the Atlantic. Its strategic location makes it one of Europe’s most accessible and used ports. The climate is Mediterranean continental, with dry summers and wet winters. Annual temperatures range from 8 °C in the north to 17 °C in the west [15]. Lisbon is highly exposed to climate risks due to Tagus estuary dynamics, with past flooding events linked to storm surges and astronomical tides [16].

The Port of Dunkirk in France spans 17 km of coastline and includes East Port (14.2 m draught) and West Port (20.5 m draught). It handles 2.4 MT annually and connects inland via the Dunkirk-Valenciennes canal for 3,000 T vessels. With a temperate climate, Dunkirk receives 747 mm rainfall annually, with average monthly extremes of 51 mm (March) and 72 mm (August). Tidal range reaches 5.6 m [17]. Flooding is often caused by strong winds lasting over 24 hours [18].

3.2. Analysis of extreme weather events in the SAFARI ports

For the following analysis, the open source Climpact software programme was used. This tool is based on ‘R’ and reads strings of meteorological big data records of rainfall and temperature. The results are given in the form of frequency, duration and magnitude of various extreme climatic events. The tool is widely used by climatologists to study climate variability and determine the impacts of climate change. The indicators calculated by Climpact are available on both monthly and annual time scales and were proposed by the World Meteorological Organization's Expert Group on Sectoral Climate Indicators (EG-SCI) in collaboration with sectoral experts.

The percentile-based indicators used in this study namely SPI, WSDI, CWD_ECF, and R95p adhere to internationally recognized standards established by the World Meteorological Organization (WMO). These indicators are defined and recommended by the WMO's Expert Team on Sector-specific Climate Indices (ET-SCI) and are detailed in the "Guidelines on the Definition and Monitoring of Extreme Weather and Climate Events" [19]. Their percentile-based structure ensures that local climatic extremes are effectively captured while maintaining comparability across different regions. The data handling procedures including threshold selection, time-scaling, and statistical interpretation follow best practices in climate data management, as outlined in WMO guidelines. In future steps, trend analysis will be carried out to investigate changes over time and then predictions of future climate conditions and their impact on ports can be made. The future climate simulations, and above-mentioned indices, based in two climate change emission scenarios (RCP 4.5 and RCP 8.5) will be analyzed to assess potential risks in port navigations [20].

Table 1: Definitions of the calculated indicators

Short name	Long name	Definition	Units
WSDI	Warm Spell Duration Indicator	Annual number of days contributing to events where 6 or more consecutive days experience Annual Maximum Temperature (TX) > 90th percentile	days
SPI	Standardised Precipitation Index	A drought measure specified as a precipitation deficit, using the SPI of 3, 6 and 12 months time scale	-
R95p	Total annual precipitation (PR) of exteme rainy days >95th percentile	Annual sum of rainfall from very wet days, of daily PR > 95th percentile	mm
CWD_ECF	Coldwave duration (CWD) as defined by the Excess Cold Factor (ECF)	The length of the longest 'coldwave' as identified by ECF. The ECF is a combination of two excess cold indices (ECI) representing the acclimitisation to cold and the climatological significance and its estimation is based on statistics (5th percentile of Average Daily Temperature) of user specified based period.	days

Seville Pilot area

Figure 3 shows the results of the calculation of SPI index. Negative values (see red points) represent periods of drought and positive values represent periods of high rainfall (see blue points). From the SPI calculation it is clear that long periods of droughts occur in the 1940s and 1980s while our trend shows that more frequent and more intense droughts occurred between 2010-2024. Regarding the positive values, i.e. wet periods, we observe their increase during the 1960-1990 decades with the indicating to us the intense rainfall episodes in these periods. In recent decades the rainfall has clearly reduced.

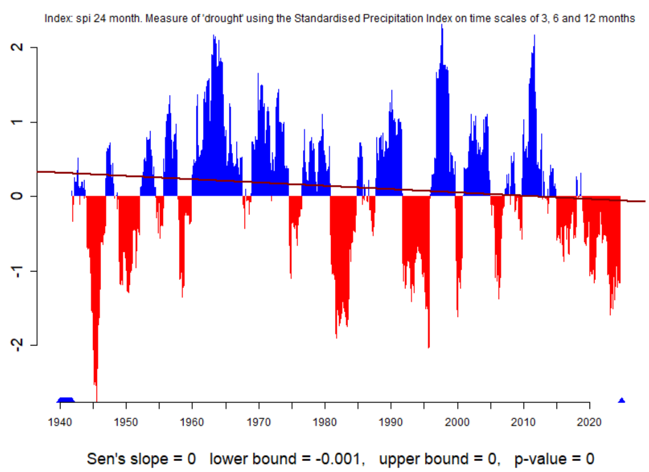

Figure 3: Standardised Precipitation Index for Seville

Figure 4 demonstrates the WSDI index which indicates the intervals during which unusually high temperatures were maintained in the Seville port for 6 or more days. The increasing trend suggests that the Seville region is becoming increasingly vulnerable to prolonged episodes of drought. Until 1980 extreme heat waves were rare. Recently there has been an increase in both the frequency and the duration of hot spells. A typical example is year 2022, when Seville experienced about 50 consecutive days of unusually high temperatures. Figure 5 depicts the CWD_ECF Index which calculates the duration of the longest cold spell for the same port. It is observed that cold spells in Seville in recent decades have become rare and their duration is short compared to the first decades (1940-1960) when the duration of cold days ranged from 20 to 30 days. Figure 6 depicts the R95p index which refers to the annual percentage of precipitation from extremely wet days that remains relatively stable with slight increases. The spikes in some years indicate that extreme weather precipitation events continue to contribute significantly to the annual precipitation rates for the Seville region. The fact that the statistical increase is not high suggests that while the region is experiencing extreme flooding episodes there is not yet observed a significant increasing trend.

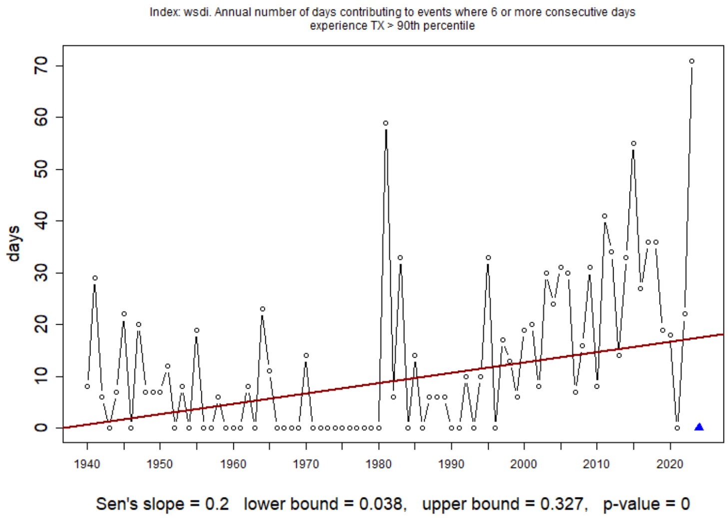

Figure 4: Warm spell duration for Seville

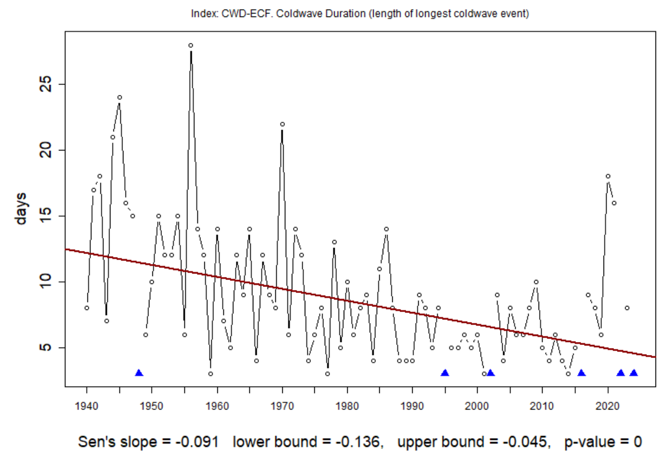

Figure 5: Cold wave duration in Seville

Lisbon Pilot area

Figure 7 shows the SPI index for Lisbon, indicating alternating wet and dry periods from 1940 to the present. In recent years, droughts have become more frequent and longer. The negative trend suggests increasing dry spells, while wet periods are becoming less frequent and less intense. The WSDI index (Figure 8) shows that since 1990, hot spells have become more frequent than in earlier decades. Strong year-to-year variability is observed, with one of the longest warm episodes recorded in 2012, lasting about 25 consecutive days. Although no clear upward trend is evident, warm spells significantly influence Lisbon's climate. The CWD_ECF index (Figure 9) indicates a decline in cold wave duration from 1940 to the present. In recent decades, cold waves have been shorter than in the past, likely due to rising regional temperatures.

Figure 10 shows the R95p index, with peaks occurring sporadically. While heavy rainfall events are present, they do not follow a consistent pattern. The overall trend remains stable, suggesting no significant change in the contribution of extremely wet days to total rainfall.

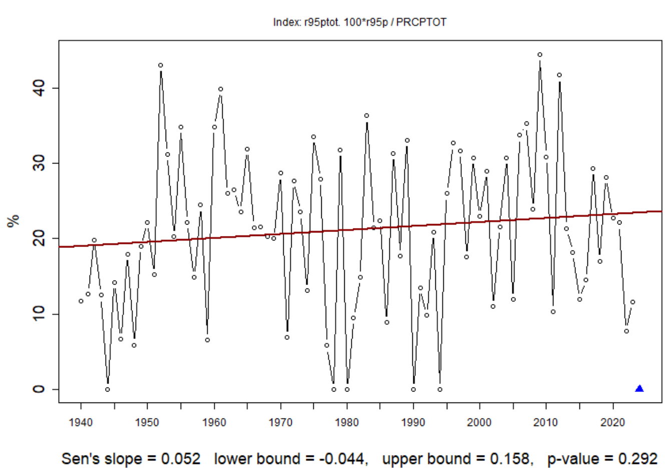

Figure 6: Total annual PR from heavy rain days in Seville

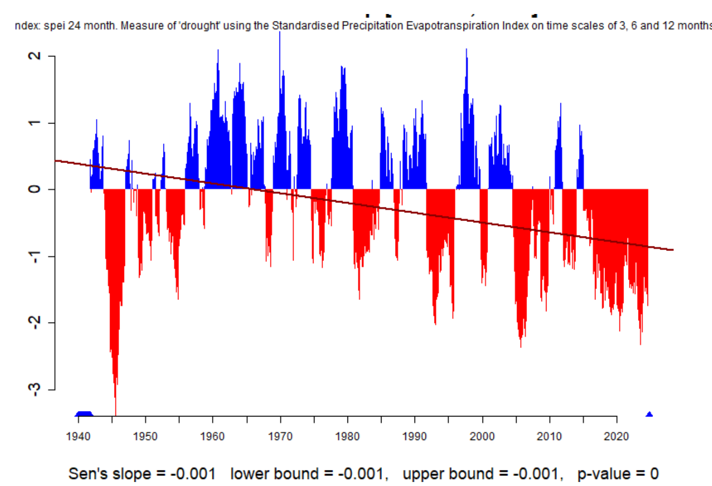

Figure 7: Standardised Precipitation Index for Lisbon

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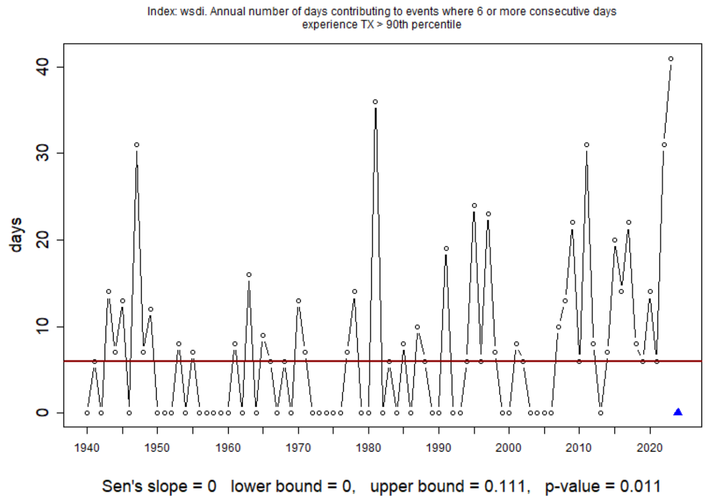

Figure 8: Warm spell duration in Lisbon

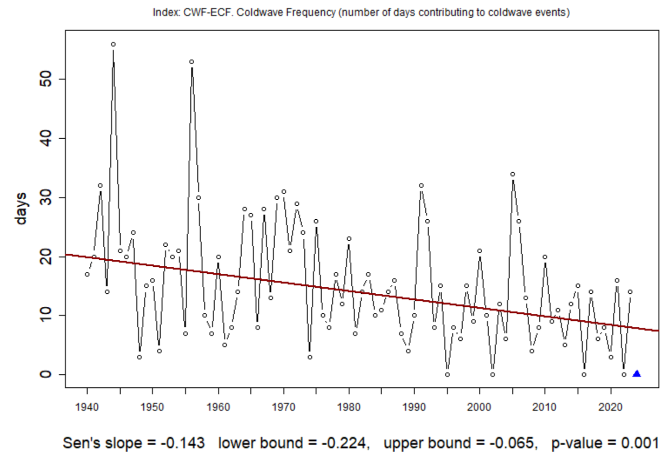

Figure 9: Cold wave duration in Lisbon

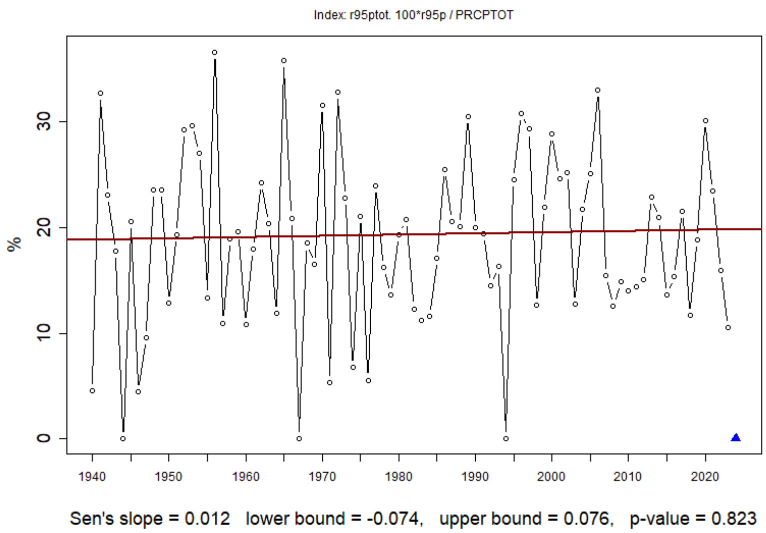

Figure 10: Total annual PR from heavy rain days in Lisbon

Dunkirk pilot area

SPI calculation for the Dunkirk region (Figure 11) indicates severe drought episodes in earlier decades, with index values reaching -2. Since 1980, both the frequency and severity of droughts have gradually declined, with shorter occurrence cycles. Concurrently, wet periods increased, peaking around 2000 when SPI values approached 2. The overall trend shows a statistically significant increase in SPI, suggesting heavier rainfall and a rising flood risk.

The WSDI index (Figure 12) reveals more frequent hot spells in recent decades. Although the overall trend appears flat, the P-value indicates statistically significant variation. This is due to sharp increases in specific intervals despite no clear long-term trend. CWD_ECF results (Figure 13) show that cold waves in the earlier decades were more frequent and longer, reaching up to 30 days. In recent decades, cold waves have declined significantly in both frequency and duration, indicating fewer and milder cold periods over time.

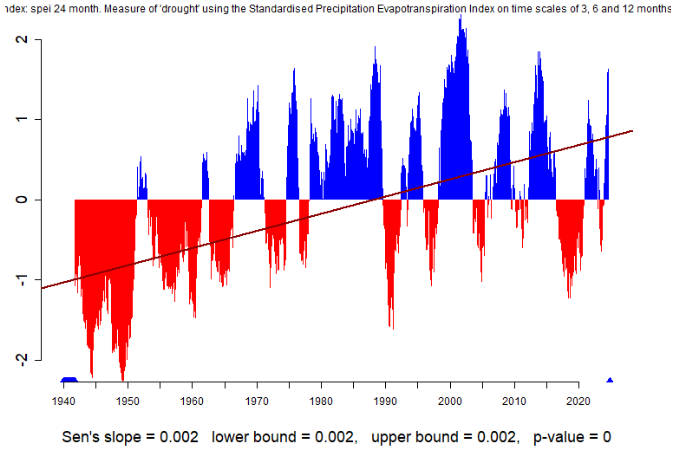

Figure 11: Standardised Precipitation Index for Dunkirk

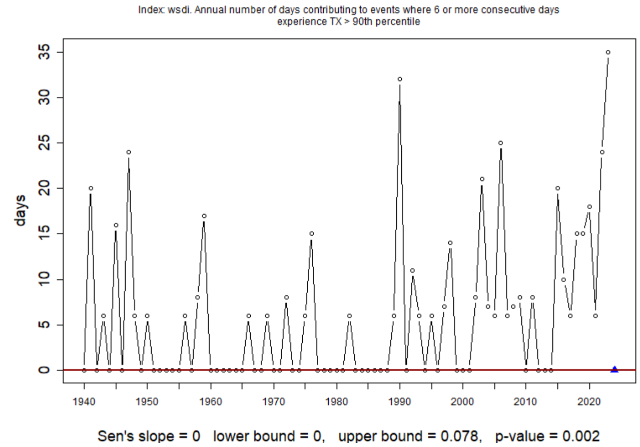

Figure 12: Warm spell duration in Dunkirk

From the calculation of *R95p* index depicted in Figure 14, it is observed that very wet days increase significantly over the years, contributing more to the annual percentage of rainfall in the region. This increasing trend indicates that there is a worrying risk of extreme hydrological events such as flooding in the region.

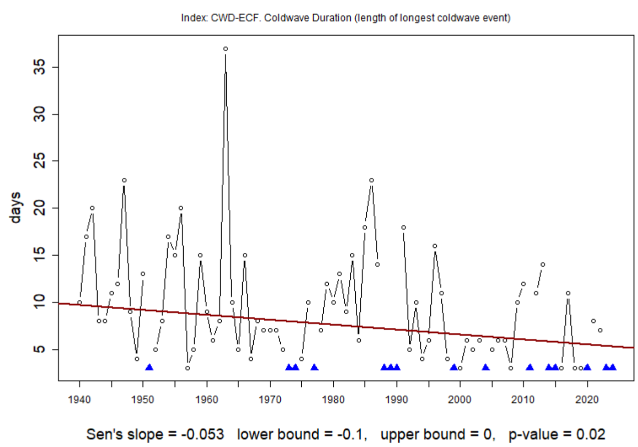

Figure 13: Cold wave duration in Dunkirk

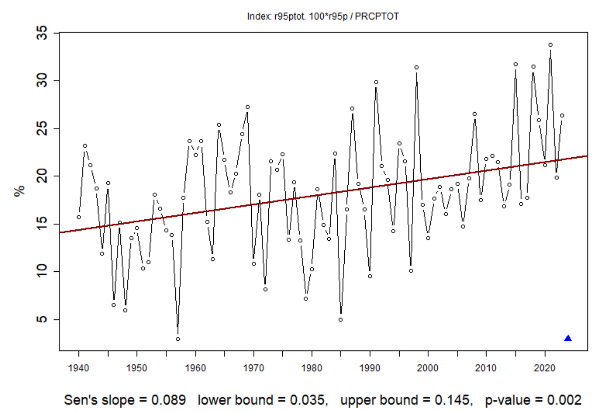

Figure 14: Total annual PR from heavy rain Days in Dunkirk

3.3. Port operation functions and stakeholders

Cargo ports generally operate with a similar set of functions essential for sustaining core operations [21,22]. The process of identifying critical port functions begins by recognizing these common functions at a generic level and then classifying them based on their criticality (e.g., critical or non-critical). Functions deemed critical are those that directly influence revenue generation, exhibit high vulnerability, or pose significant safety risks. Additionally, the relevant stakeholders responsible for or affected by these functions are identified. At a high level of abstraction, the identified primary functions of port terminal operations are illustrated in the following figure. Further refinement and detailed classification will be conducted in collaboration with port stakeholders, involving port and terminal operators in the SAFARI project. The port infrastructure required to perform each of these functions are classified in Table 2. These infrastructures were extracted from the data provided by the SAFARI ports on the terminals and their equipment.

Table 2: Port infrastructure of the identified functions

Function	Infrastructure
Dock operations	Berths, quay walls, Ship-To-Ship cranes, mooring systems, fenders, lighting, freshwater/bunkering, waste disposal
Dock transport	Terminal trailers, internal roadways, Rail-Mounted Gantry cranes, rail sidings, conveyor systems, container chassis
Yard operations	Stacking areas, Rubber-Tired Gantry/ Rail-Mounted Gantry cranes, reefer stations, straddle carriers, hazardous storage, maintenance areas
Gate operations	Gate complexes, automated systems, weighbridges, inspection facilities, staging areas
IT and Admin functions	Digital platforms (terminal operating systems, port operating system), cybersecurity infrastructure, administrative offices, emergency response centres
Utility functions	Electricity grid, shore power, renewable energy cites, freshwater systems, wastewater treatment, stormwater systems, mobile telecommunication network, internet

As part of defining the ICS, port operations stakeholders were identified, and their roles are depicted in Table 3. These are only the stakeholders involved in cargo handling, intermodal freight transport, and port security and access control. However, other stakeholders and their roles are not defined yet due to the overlap they might have and their dependency on specific ports. These will be later defined in workshops with each port authority stakeholder.

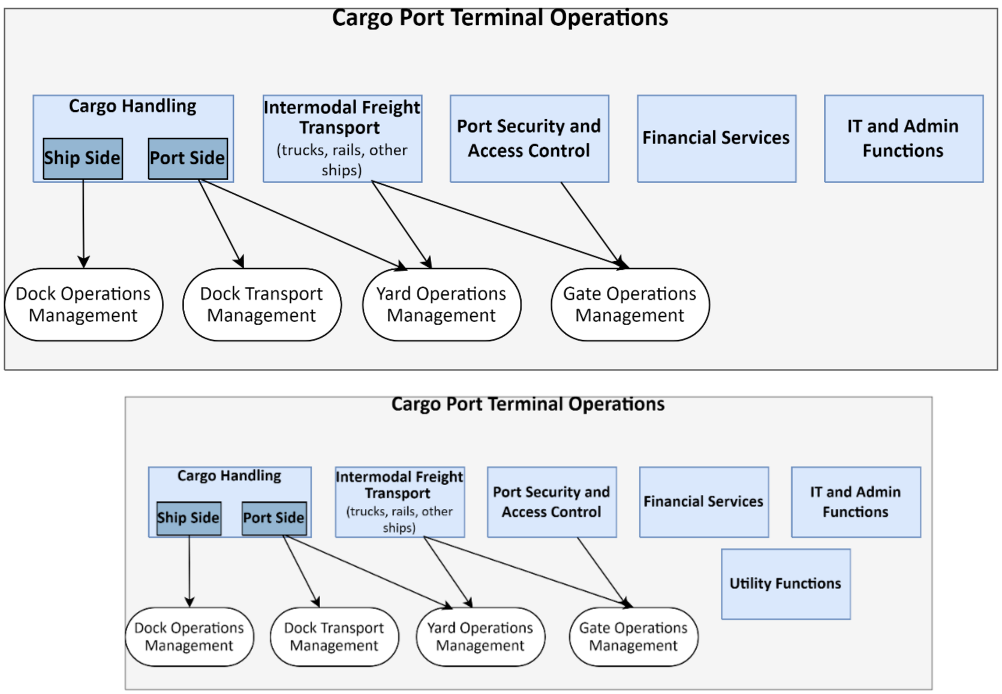

Figure 15: Port operations main functions

Table 3: Port operations stakeholders and roles, adapted from [21,22]

Stakeholder Name	**Stakeholder Role**
Port Authority	Administers port property, terminals, and facilities.
Port Operations Manager	Manages port facilities, safety, security, and resource allocation.
Terminal Operator	Leases terminal facilities; may provide cargo-handling equipment.
Terminal Operations Manager	Oversees terminal operations to optimize resources and maintain standards.
Gate Operations Manager	Manages gate and terminal transfer activities; liaises with stakeholders.
Drayage Company	Handles intermodal transportation of containers.
Drayage Truck Driver Scheduler	Schedules truck drivers for container transport.

Drayage Truck Driver	Transports containers to/from warehouses and terminals.
Terminal Trailer Driver	Moves containers within the terminal.
Crane Operator Scheduler	Assigns crane operators for container handling.
Crane Operator	Operates cranes to load/unload containers.
Operations Officer	Ensures safe vessel transit and port operations.
Security Officer	Protects people, property, and information at the port.
Gate Control Employee	Manages gate access as part of port authority.
Harbor Master	Establishes and manages berthing schedules.
Marine Pilot	Navigates ships safely in port waters.
Tugboat Pilot	Steers larger ships in tight spaces using tugboats.

Recent extreme weather trends (Section 3.2) show increased rainfall in Dunkirk, raising flood risks. In contrast, Lisbon and Seville are experiencing severe droughts and reduced wet periods. All three regions have seen a rise in heatwave duration and a weakening of cold periods. Based on these trends and the infrastructure listed in Table 2, the following vulnerabilities are identified:

Dunkirk (Flood risk):

- Direct impact: Internal roadways, Hazardous storage
- Indirect impact: Renewable energy sites, Stormwater and wastewater systems

Lisbon and Seville (Heat risk):

- Direct impact: STS cranes, RMG cranes, RTG cranes, Rail sidings
- Indirect impact: Power grid, Shore power, Freshwater systems

Mapping these to Table 2 functions highlights potentially affected operations:

- Dunkirk: Dock transport, Yard operations, Utility functions
- Lisbon & Seville: Dock operations, Dock transport, Yard operations, Utility functions

These results are preliminary and will be validated through expert workshops with port stakeholders. A more detailed analysis using structured expert elicitation will define additional ICS stakeholder roles.

4. Conclusion

This study investigates the vulnerability and resilience of three European ports namely Seville, Lisbon, and Dunkirk using a combined framework of vulnerability analysis and recovery planning. Historical and projected climate data were analysed using Climpact software, focusing on SPI, WSDI, CWD_ECF, and R95p indicators. Results show increasing drought and heatwave frequency in Seville, more variable heat and reduced coldwaves in Lisbon, and significantly rising precipitation in Dunkirk which suggests increased flood risk. Port functions were also identified and linked to critical infrastructure and stakeholders. Based on initial climate analysis, potentially affected infrastructure was mapped to port functions requiring recovery actions.

Future work will analyse projected climate conditions, identify vulnerable infrastructure, and define corresponding recovery actions. An Incident Command Structure (ICS) will be developed, and a simulation model will evaluate the effectiveness of recovery strategies. Stakeholder input will support validation and iterative refinement of recovery plans.

5. Acknowledgments

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References

[1] J.S. Santos, C.K. Parise, L. Duarte, & A.C. Teodoro, Bibliometric Analysis of Global Research on Port Infrastructure Vulnerability to Climate Change (2012–2023): Key Indices, Influential Contributions, and Future Directions. *Sustainability*, *16*(19), Article 19, 2024.

[2] ESPO. (2024). *ESPO Environmental Report 2024*. https://www.espo.be/media/ESP-3254_Sustainability%20Report%202024-BW-HR-printable%20version.pdf

[3] UNCTAD. (2024b). *PART II - Port disruption and resilience: A closer look | United Nations*. Available on https://resilientmaritimelogistics.unctad.org/guidebook/part-ii-port-disruption-and-resilience-closer-look

[4] J. Verschuur, E.E. Koks, & J.W. Hall, Multi-hazard risk to global port infrastructure and resulting trade and logistics losses. *Communications Earth & Environment*, *4*(1), 2023, 1–12.

[5] S. Kasthala, D. Parthasarathy, K. Narayanan, & A.B. Inamdar, Classification and Evaluation of Current Climate Vulnerability Assessment Methods. *Social Indicators Research*, *171*(2), 2024, 605–639.

[6] M. Vousdoukas, L. Mentaschi, E. Voukouvalas, M. Verlaan, & L. Feyen, Extreme Sea levels on the rise along europe's coasts. Earth S Future, 5(3), 2017, 304-323.

[7] Z. Shen, X. Xu, J. Li, & S. Wang, Vulnerability of the maritime network to tropical cyclones in the northwest pacific and the northern indian ocean. Sustainability, 11(21), 6176. 2019.

[8] UNCTAD. (2024a). *1.2 Extreme Weather Events | United Nations*. Available on https://resilientmaritimelogistics.unctad.org/guidebook/12-extreme-weather-events

[9] J. Verschuur, E.E. Koks, & J.W. Hall, Systemic risks from climate-related disruptions at ports. *Nature Climate Change*, *13*(8), 2023, 804–806.

[10] A. Becker, and M. Caldwell, Stakeholder perceptions of seaport resilience strategies: a case study of gulfport (mississippi) and providence (rhode island). Coastal Management, 43(1), 2015, 1-34.

[11] R, Der Sarkissian, M.J. Al Sayah, C. Abdallah, J.M. Zaninetti, & R. Nedjai, Land use planning to reduce flood risk: opportunities, challenges and uncertainties in developing countries. *Sensors*, 2022, *22*(18), 6957.

[12] C. Arango, P. Cortés,J. Muñuzuri, and L. Onieva, Berth allocation planning in Seville inland port by simulation and optimisation. Advanced Engineering Informatics, 25(3), 2011, pp.452–461.

[13] Confederación Hidrográfica del Guadalquivir. Plan Hidrológico de la Demarcación Hidrográfica del Guadalquivir. Segundo ciclo de planificación: 2016 - 2021. Anejo Nº 2. Descripción general de la Demarcación. Gobierno de España. Ministerio de Agricultura, Alimentación y Medio Ambiente. Confederación Hidrográfica del Guadalquivir, 2015.

[14] M. Borrego-Marín, J. Perales, A. Posadillo, C. Gutiérrez-Martín, &, Analysis of Guadalquivir droughts 2004–2012 based on SEEA-W tables. In DROUGHT: Research and Science-Policy Interfacing, Proceeding of the International Conference on DROUGHT: Research and Science-Policy Interfacing. Leiden, The Netherlands: CRC Press. 2015

[15] G. Mezger, L. De Stefano, M. González Del Tánago, Analysis of the Evolution of Climatic and Hydrological Variables in the Tagus River Basin, Spain. Water 14, 818, 2022.

[16] C. Antunes, C. Rocha, C. Catita, Coastal Flood Assessment due to Sea Level Rise and Extreme Storm Events: A Case Study of the Atlantic Coast of Portugal's Mainland. Geosciences 9, 239. 2019.

[17] A. Maspataud, M. Ruz, S. Vanhée, Potential impacts of extreme storm surges on a low-lying densely populated coastline: the case of Dunkirk area, Northern France. Nat Hazards 66, 2013, 1327–1343.

[18] M.H. Ruz, A. Hequette, A. Maspataud, Identifying Forcing Conditions Responsible for Foredune Erosion on the Northern Coast of France. Journal of Coastal Research 56, 356–360, 2009.

[19] World Meteorological Organization, (2023). *Guidelines on the definition and characterization of extreme weather and climate events* (WMO-No. 1310). Available on https://library.wmo.int/records/item/58396-guidelines-onthe-definition-and-characterization-of-extreme-weather-and-climate-events

[20] Intergovernmental Panel on Climate Change. In: Summary for Policymakers. T.F. Stocker, D. Qin, G.K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, P.M. Midgley, editors. Cambridge University Press; Cambridge, United Kingdom, and New York, NY, USA: 2013. p. 28.

[21] S. Haraldson, M. Lind, S. Breitenbach, J.C. Croston, M. Karlsson, & G. Hirt, The Port as a Set of Socio-technical Systems: A Multi-organisational View. In *Maritime Informatics*, Springer, Cham, 2021, (pp. 47–63).

[22] V. Romero, & E. Fernandez, Towards a Reference Architecture for Cargo Ports. *Future Internet*, *15*(4), Article 4. 2023.

[23] A.O. Tavares, P.P.D. Santos, P. Freire, A.B. Fortunato, A. Rilo, L. Sá, Flooding hazard in the Tagus estuarine area: The challenge of scale in vulnerability assessments. Environmental Science & Policy 51, 2015,238–255.