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Beyond Rerouting: Resilience and Dependency in Sustainable Port–Hinterland Logistics

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Abstract

Maritime disruptions increasingly redirect vessels and cargo towards alternative routes and ports. Although rerouting can preserve connectivity, its effectiveness cannot be assessed through route availability or port capacity alone, as redirected flows may generate new constraints and dependencies within the resulting logistics configuration. This study examines how maritime rerouting reconfigures logistics dependencies and under which conditions alternative ports provide effective rather than merely nominal substitutability. A comparative case-study approach is applied to five European ports—Algeciras, Valencia, Barcelona, Rotterdam and Sines—following the Red Sea crisis. The study develops a Post-Rerouting Sequential Stress Test (PR-SST) combining maritime connectivity and port capacity with function-specific gateway and transhipment pathways, while incorporating sustainability as a cross-cutting dimension. The framework is operationalised through a Post-Rerouting Sequential Assessment (PR-SA), which applies its sequential diagnostic logic to the five selected ports using quantitative indicators and documentary evidence. The analysis distinguishes nominal capacity from effective substitutability and introduces post-rerouting dependency to capture dependencies that emerge or intensify following adaptation. The comparative assessment indicates that port capacity and maritime connectivity alone are insufficient to establish effective substitutability across the five ports. Instead, substitutability depends on the functional role of each port and the continuity of the subsequent logistics pathway, while post-rerouting dependencies may constrain alternative configurations. The findings illustrate how the PR-SST can support the assessment of logistics constraints and dependencies beyond the level of individual ports. The framework therefore extends resilience assessment beyond maritime rerouting and individual port capacity to the integrated logistics configuration through which redirected flows continue.

Keywords: maritime rerouting; port–hinterland logistics; resilience; effective substitutability; post-rerouting dependency; transhipment; sustainable logistics

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1. Introduction

Maritime transport is a fundamental component of global supply chains, connecting production centres and consumer markets through increasingly interdependent transport

and logistics networks [1]. Within these networks, ports function not merely as interfaces between sea and land, but as critical nodes linking maritime services to hinterland transport, logistics infrastructure and inland markets [2,3]. Their performance therefore depends on the effective integration of maritime connectivity, terminal capacity, inland transport networks and logistics services [2]. Accordingly, the sustainability of port logistics increasingly encompasses the capacity of port–hinterland systems to maintain functionality under disruption and adapt to changing trade and transport patterns [2,4].

Recent disruptions affecting major maritime corridors have highlighted the vulnerability of global supply chains to geopolitical conflict, climate-related events, infrastructure failures and operational constraints [5,6]. When established routes become unavailable, unsafe or economically unattractive, shipping networks adapt through rerouting, alternative ports and the redistribution of cargo flows [5–7]. While such responses can preserve connectivity and mitigate immediate disruption [6,7], they also change the geography of logistics, increasing the strategic importance of alternative ports and subsequent maritime and inland connections while placing additional pressure on the logistics systems through which redirected cargo must continue [6–8].

Much of the literature on maritime and port resilience has focused on network redundancy, alternative routes and infrastructure, port capacity, and the ability to maintain or recover functionality following disruption [9–11]. However, these dimensions do not fully capture what happens after redirected flows reach an alternative port. A port may have sufficient capacity to accommodate additional traffic while the wider logistics system lacks the ability to redistribute the resulting cargo efficiently. Depending on the function performed by the port, this redistribution may occur through hinterland transport systems or through onward maritime services. Port–hinterland resilience depends on interconnected infrastructure and services, including road and rail networks, intermodal terminals and inland logistics facilities [2,4,12]. Constraints within these components may limit the ability of the wider logistics chain to absorb additional flows [2,12]. Consequently, the existence of an alternative port does not necessarily imply the existence of an effective alternative logistics configuration.

This distinction suggests the need to differentiate between nominal capacity and effective substitutability. Nominal capacity refers to the ability of an alternative node to accommodate additional flows, whereas effective substitutability requires the resulting logistics configuration to absorb and redistribute those flows without generating disproportionate congestion, inefficiency or new critical dependencies. This distinction also has sustainability implications: port–hinterland transport generates externalities associated with emissions, congestion and infrastructure pressure [13–15], while crisis-induced rerouting can increase transport distances, operating costs and emissions while redistributing environmental pressures across ports and corridors [16,17]. An adaptive response that preserves maritime flows may therefore maintain immediate connectivity while reconfiguring network dependencies and generating additional costs elsewhere in the logistics system [16,18].

Although previous studies have examined maritime rerouting, port substitutability, and network dependencies, these approaches tend to focus on distinct dimensions of disruption response. Research on maritime rerouting primarily addresses the availability of alternative routes and the reconfiguration of maritime connections, while studies on port capacity and substitutability assess whether alternative ports can accommodate redirected flows [9–11]. Network-based approaches, in turn, highlight the interdependencies through which disruptions may propagate across transport and logistics systems [13–16]. However, these perspectives do not fully explain whether rerouted flows can maintain continuity beyond the alternative port itself. The availability of maritime access and port capacity does not necessarily guarantee effective onward movement, as continuity also

depends on terminal operations, hinterland accessibility, logistics services, and connections to subsequent destinations. These constraints may differ according to the role of the alternative port as a gateway or a transhipment hub. The research gap therefore lies in the need to connect maritime rerouting and port substitutability with the successive operational requirements and network dependencies that determine whether redirected flows can be sustained across the wider logistics pathway, while also accounting for the potential sustainability implications of rerouting, including additional transport activity, costs, and emissions [13–18].

Against this background, this study develops a conceptual and analytical framework for assessing resilience and dependency in sustainable logistics following maritime rerouting. It addresses two research questions: (1) How does maritime rerouting reconfigure dependencies across the logistics systems that follow alternative ports? and (2) Under what conditions does an alternative port provide effective rather than merely nominal substitutability? The study contributes to the literature by introducing post-rerouting dependency as an analytical perspective for examining how redirected flows reconfigure logistics networks; distinguishing nominal capacity from effective substitutability at the system level; and proposing a Post-Rerouting Sequential Stress Test (PR-SST) that follows redirected flows through common maritime and port dimensions and subsequent gateway and transhipment pathways, with sustainability incorporated as a cross-cutting dimension.

The PR-SST therefore provides a structured assessment of the constraints affecting flow continuity along the relevant logistics pathway, without aggregating the results into an overall port performance ranking.

The remainder of the paper is organised as follows. Section 2 presents the conceptual background, reviewing the literature on maritime disruption and network resilience, ports as integrated maritime–hinterland nodes, effective substitutability, and post-rerouting dependency and sustainable logistics. Section 3 describes the research design, case selection, PR-SST framework, and assessment procedure. Section 4 presents the comparative assessment of the five selected European ports. Section 5 discusses the main findings, their implications and the limitations of the study. Finally, Section 6 presents the conclusions and directions for future research.

2. Conceptual Background: From Maritime Rerouting to Port–Hinterland Dependency

The literature review is organised around four interconnected themes that provide the conceptual basis for the PR-SST framework. First, research on maritime disruption, rerouting and network resilience explains how shipping networks respond to external shocks and preserve connectivity [19–21]. Second, studies of ports as maritime–hinterland nodes highlight the role of terminal operations, inland transport and logistics services in maintaining the continuity of cargo flows [2,4,12]. Third, the literature on port capacity and substitutability helps distinguish the availability of alternative infrastructure from the ability of an alternative port to support the effective redistribution of cargo [9–11]. Finally, research on network dependencies and sustainable logistics provides the basis for examining how rerouting may create new bottlenecks and redistribute operational and environmental pressures across transport systems [13–18]. These themes are considered together because the resilience of a rerouted flow depends not only on the capacity of the alternative port, but also on the successive connections and operational conditions required to move cargo towards its destination or onward maritime connection.

2.1. Maritime Disruption, Rerouting and Network Resilience

Maritime transport networks are increasingly exposed to disruptions arising from geopolitical tensions, extreme weather events, infrastructure failures and operational constraints, whose effects can propagate across interconnected transport and supply chain networks [19,22]. In this context, resilience refers to the capacity of maritime transport systems to withstand disruption, maintain essential functions and adapt or recover while preserving the movement of goods [22]. Redundancy, route diversification and the availability of alternative corridors and nodes therefore constitute important mechanisms through which maritime networks can respond to disturbances and maintain connectivity [19,22].

Rerouting represents one of the most visible forms of such adaptation. When established maritime corridors become unavailable, unsafe or operationally unattractive, vessels and cargo may be redirected through alternative routes, modifying sailing distances, transit times, service configurations and patterns of port connectivity [18,19]. Recent evidence from the Red Sea crisis illustrates these effects particularly clearly. The diversion of services around the Cape of Good Hope altered the structure of European maritime connectivity and produced differentiated effects across gateway, hub and feeder ports [18]. From a network perspective, rerouting can therefore preserve the movement of goods without reproducing the original configuration of the transport system, as traffic is redistributed across routes and nodes and the relative importance of individual ports and corridors changes [18].

This distinction is important for the assessment of resilience. The successful continuation of maritime flows demonstrates adaptive capacity, but does not necessarily imply that the resulting logistics configuration is equally resilient or sustainable. Rerouting may increase sailing distances and transport costs and modify the distribution of traffic across ports and corridors [18,19]. Empirical evidence from the Red Sea crisis shows that these changes can affect both maritime connectivity and transport-chain costs, while port-level responses to the same disruption can differ substantially [7,18]. Resilience assessment should therefore consider not only whether connectivity is maintained, but also how and through which configuration that connectivity is maintained.

While maritime rerouting constitutes the initial adaptive response examined in this study, the analysis focuses particularly on what occurs once redirected flows reach an alternative port. At this point, the effectiveness of the alternative depends not only on maritime connectivity and port performance, but also on the capacity of the subsequent logistics system to accommodate and redistribute additional flows, either through hinterland connections or onward maritime services. Recent port-resilience research supports the relevance of this transition by identifying hinterland connectivity, alongside geographical location and network embedding, as a factor influencing port resilience under geopolitical disruption [7]. The port therefore represents the interface between maritime adaptation and the wider logistics response, shifting the analytical focus from the availability of an alternative maritime route towards the capacity of the resulting logistics configuration to support that alternative.

2.2. Ports as Integrated Maritime–Hinterland Nodes

Ports are no longer understood solely as maritime terminals where cargo is transferred between ships and land-based transport. Their role has progressively evolved towards that of integrated logistics nodes embedded in wider transport and supply chain networks, connecting maritime services with inland transport corridors, intermodal terminals, logistics platforms and final markets [2,20]. The concept of port regionalization captured this evolution by showing that the functional development of ports increasingly

extends beyond the traditional port perimeter and depends on their integration with inland freight distribution systems [20].

However, the role performed by ports within these networks is not uniform. Ports may function as gateways, connecting maritime flows with their hinterlands, or as transhipment hubs, where containers are transferred between maritime services before continuing towards another port. Major container ports may combine both functions, although their relative importance varies according to network configuration and shipping strategies [23]. The distinction is particularly relevant under rerouting conditions because additional flows reaching an alternative port do not necessarily generate equivalent pressure on its hinterland: gateway cargo must be transferred towards inland destinations, whereas transhipment cargo may be redistributed through onward maritime services [21,24].

For gateway flows, port performance depends not only on terminal infrastructure and handling capacity but also on the quality and configuration of hinterland connections. Road and rail accessibility, inland terminals and intermodal logistics facilities influence how efficiently cargo can move between the maritime gateway and inland origins and destinations [2,21]. For transhipment flows, by contrast, the effectiveness of the port depends more strongly on terminal transfer capacity and onward maritime connectivity [24]. The logistics implications of additional traffic therefore depend not only on how much cargo a port receives, but also on the function performed by that port within the adapted network.

Constraints affecting one component can influence the performance of the wider chain, while additional port capacity may provide limited benefits if either onward maritime connections or inland logistics systems become the binding constraint [2,25]. For the purposes of this study, the port is consequently considered an interface at which redirected maritime flows may either be redistributed through maritime services or transferred into the hinterland logistics system. This distinction provides the basis for assessing whether an alternative port represents an effective substitute within the reconfigured transport network.

2.3. From Port Capacity to Effective Substitutability

Port capacity is a critical factor in determining the ability of a port to accommodate additional cargo flows, particularly when disruptions alter established traffic patterns and generate unexpected increases in demand. Terminal throughput, berth and yard capacity, storage availability and operational efficiency influence the extent to which additional traffic can be handled without generating excessive congestion or delays [8,26]. Under disruption, these constraints become particularly relevant because redirected flows may produce sudden peaks in demand at receiving ports, potentially affecting port operations and subsequent cargo movements [8].

However, the ability of a port to physically accommodate additional traffic does not necessarily mean that it can function as an effective substitute within the reconfigured logistics network. Gateway cargo must be transferred efficiently through inland transport networks, intermodal terminals, logistics facilities and distribution systems, whereas transhipment cargo depends on terminal transfer capacity and the availability and connectivity of onward maritime services [24]. Capacity constraints may therefore emerge either within the hinterland system or in subsequent maritime connections, even when sufficient terminal capacity is available [9,25]. In this sense, port capacity represents a necessary but not sufficient condition for effective substitution.

Building on this distinction, this study differentiates between nominal capacity and effective substitutability. Nominal capacity refers to the ability of an alternative port to receive and handle additional flows based primarily on its available infrastructure and

operational capacity. Effective substitutability, by contrast, refers to the ability of the wider logistics configuration to absorb and redistribute redirected flows towards their subsequent destinations while maintaining acceptable levels of functionality and without generating critical bottlenecks or disproportionate new dependencies. Effective substitutability is therefore conceptualized here as a system-level property, rather than an attribute of the port considered in isolation.

Importantly, effective substitutability is both sequential and function-dependent. Research on port–hinterland networks demonstrates that capacity constraints can arise at different links and nodes and that limitations in one component can affect the performance of the wider logistics chain [9,23,25]. Adequate capacity at one stage cannot therefore compensate indefinitely for a critical constraint at another. A port may appear to provide a viable alternative when assessed through terminal capacity alone, while a bottleneck emerges at the next stage of the adapted logistics chain.

This perspective changes the analytical question posed by maritime rerouting. Rather than asking only whether an alternative port exists or possesses sufficient capacity, the relevant question becomes whether the resulting logistics configuration can sustain and redistribute redirected flows according to the function performed by the alternative port. Effective substitutability thus provides the conceptual link between maritime adaptation and the post-rerouting dependencies that may emerge within the reconfigured transport system. This sequential perspective provides the conceptual basis for the assessment framework developed in Section 3.

2.4. Post-Rerouting Dependency and Sustainable Logistics

Maritime rerouting changes more than the geographical path followed by vessels. By redirecting cargo towards alternative corridors and ports, it can also modify the distribution of flows, infrastructure utilisation and logistics activity across the wider transport system [7,18,19]. These changes may reduce exposure to the initial disruption while simultaneously increasing reliance on alternative ports, onward maritime services, inland corridors and logistics infrastructure. The resulting configuration may therefore preserve connectivity while creating a different pattern of dependencies across the transport network [7,19].

This study refers to this phenomenon as post-rerouting dependency: the set of dependencies that emerges or becomes more significant after maritime flows are redirected through an alternative logistics configuration. The concept shifts attention from the immediate success of rerouting towards the structure that results from adaptation. A redirected flow may bypass the original disruption successfully but become increasingly dependent on a particular port, onward maritime service, rail corridor, road connection, intermodal terminal or logistics node. Post-rerouting dependency does not therefore imply that adaptation has failed; rather, it recognises that successful adaptation can alter where and how the system becomes dependent.

These reconfigured dependencies also have implications for sustainability. Maritime rerouting can increase sailing distances, fuel consumption, transport costs and emissions, while the concentration of additional cargo at alternative ports may increase congestion and place additional pressure on the subsequent logistics system [16,17]. The environmental consequences may extend beyond the maritime leg of the journey. If redirected flows depend more heavily on road transport, require longer inland distances or generate congestion at ports and logistics corridors, the alternative configuration may preserve supply chain continuity while producing additional environmental and operational externalities [13,17]. Resilience and sustainability should therefore not be treated as independent properties of the adapted logistics system.

From this perspective, a sustainable response to maritime disruption requires more than the availability of an alternative route or sufficient capacity at an alternative port. It requires an integrated logistics configuration capable of accommodating and redistributing redirected flows without generating disproportionate operational, infrastructural or environmental pressures elsewhere in the system. The concepts of effective substitutability and post-rerouting dependency are therefore complementary: the former evaluates whether an alternative configuration can effectively support redirected flows, while the latter identifies the dependencies that arise from doing so. Together, they provide the conceptual basis for assessing whether rerouting contributes to system-wide resilience and sustainability or primarily relocates constraints within the logistics network.

Recent research has highlighted the importance of integrating environmental performance into port assessment, particularly through measures aimed at reducing energy consumption and carbon emissions. Issa Zadeh et al. [27] examine the role of smart energy infrastructure in reducing the carbon footprint of ports, while Issa Zadeh et al. [28] review decarbonisation measures involving energy management systems, equipment, infrastructure, and environmental policies. These contributions reinforce the need to consider environmental performance alongside operational capacity when assessing port systems. In the context of the PR-SST framework, this perspective is particularly relevant because the redistribution of cargo following maritime rerouting may alter energy requirements and environmental pressures across ports and their associated logistics pathways. Accordingly, the availability of nominal terminal capacity should not, on its own, be interpreted as evidence of sustainable substitutability; the assessment must also recognise the operational and environmental conditions under which redirected flows can be accommodated.

Table 1 summarises the main strands of literature reviewed in this section, grouping the relevant studies according to their thematic contributions to the conceptual development of the PR-SST framework. The classification highlights the complementary roles of maritime network resilience, port–hinterland integration, effective substitutability, and post-rerouting dependency and sustainability.

Table 1. Thematic classification of the literature underpinning the PR-SST framework.

Literature Category	Main Research Focus	References
Maritime disruption, rerouting and network resilience	Disruption response, route diversification, maritime connectivity and network adaptation	[7,18,19,22]
Ports as integrated maritime–hinterland nodes	Port regionalization, gateway and transhipment functions, hinterland connectivity and logistics integration	[2,20,21,23–25]
Port capacity and effective substitutability	Terminal capacity, operational constraints, alternative port capacity and logistics pathway continuity	[8,9,23–26]
Post-rerouting dependency and sustainable logistics	Reconfigured network dependencies, transport externalities, emissions, congestion and port decarbonisation	[7,13,16–19,27,28]

Note: References follow the numbering used in the manuscript. Some studies contribute to more than one thematic category.

3. Methodology

3.1. Research Design and Case Selection

This study adopts a comparative case-study design to examine whether maritime rerouting translates into effective substitutability within reconfigured logistics networks. The empirical setting is provided by the reorganisation of container shipping services following the Red Sea crisis, which led major carriers to divert services from the Suez Canal towards the Cape of Good Hope, altering sailing distances, service patterns and port connectivity between Asia and Europe [18,19]. Rather than assessing the maritime disruption

itself, the analysis focuses on what occurs when redirected flows reach alternative ports and how the subsequent movement of cargo is conditioned by the function performed by those ports within the adapted network.

The case selection follows a purposive, variation-oriented approach. Ports are selected according to four criteria: (i) documented exposure to changes in maritime connectivity associated with the Red Sea rerouting; (ii) differences in geographical position and maritime network role; (iii) differences in the relative importance of gateway and transhipment functions; and (iv) availability of comparable secondary data on maritime connectivity, port activity and onward maritime or hinterland connections. This approach allows the analysis to examine whether effective substitutability differs according to both the capacity of the alternative port and the function it performs within the reconfigured logistics network.

The comparative analysis includes Algeciras, Valencia, Rotterdam, Barcelona and Sines. The first four provide variation in geographical position, network embeddedness and hinterland configuration and have been examined in previous research on the effects of the Red Sea crisis on European port resilience and connectivity [7,18]. Sines is included as a complementary case because of the importance of transhipment in its container traffic and its strategic position on major deep-sea shipping routes, allowing the analysis to examine more explicitly the relationship between transhipment and hinterland dependency. The comparison therefore does not assume that all redirected cargo follows the same logistics pathway after reaching an alternative port.

The study relies on secondary data obtained from port authorities, Eurostat, UNCTAD, European transport databases and published scientific literature. Where available, indicators are examined before and after the onset of the Red Sea crisis to identify changes associated with the rerouting episode. The purpose is not to rank ports according to overall performance, but to identify where constraints and dependencies emerge after rerouting and whether these differ between gateway-oriented and transhipment-oriented logistics configurations.

3.2. Post-Rerouting Sequential Stress Test and Post-Rerouting Sequential Assessment

The PR-SST provides the analytical framework for assessing whether an alternative logistics configuration can accommodate and redistribute cargo flows following maritime rerouting, identifying the stages at which constraints or new dependencies may emerge. Rather than evaluating port capacity as an isolated attribute, the PR-SST follows redirected flows sequentially through the interconnected components required for their continued movement towards subsequent destinations [2,7]. The PR-SA operationalises this framework through an evidence-based diagnostic assessment of port–hinterland pathway resilience following maritime rerouting. In this study, the PR-SST refers to the conceptual framework defining the sequential dimensions and diagnostic logic of the analysis, whereas the PR-SA refers to its empirical application to the selected ports using the available quantitative indicators and documentary evidence.

The methodological contribution of the proposed approach lies not in the individual assessment of maritime connectivity, port capacity or hinterland accessibility, which are already established dimensions in the literature, but in their integration into a function-specific, sequential and non-compensatory assessment of post-rerouting logistics configurations. While the PR-SST establishes the analytical structure for identifying potential constraints and emerging dependencies across successive logistics stages, the PR-SA provides the procedure for applying this structure to individual port cases using the available empirical evidence. Together, they extend conventional port-centred assessments towards the evaluation of effective logistics pathway continuity, distinguishing gateway and

transhipment requirements and examining whether maritime adaptation preserves system-wide functionality or creates new dependencies elsewhere in the transport network.

The assessment begins with two dimensions common to all redirected flows: maritime connectivity and port capacity. Maritime connectivity captures the ability of the alternative port to receive redirected services and remain connected to relevant shipping networks, whereas port capacity assesses whether terminal infrastructure and operations can accommodate additional traffic without creating critical congestion or delays [7,26]. These dimensions establish whether redirected flows can reach and be processed by the alternative port.

For operational purposes, effective substitutability refers to the ability of an alternative port and its associated logistics pathway to receive redirected flows and maintain their onward movement through the relevant stages. Its assessment draws on the available evidence concerning maritime service availability and port operations, complemented, according to the function performed, by evidence on hinterland accessibility and logistics capability for gateway traffic, or terminal transfer capability and onward maritime connections for transhipment traffic. Post-rerouting dependency refers to the emergence or intensification of reliance on specific ports, corridors, terminal interfaces, maritime services, or onward connections following the reconfiguration of cargo flows. It is assessed by identifying such dependencies in the available evidence and examining whether alternative connections are documented. Potential constraints are identified where the available evidence indicates that limitations at a given stage may prevent or materially restrict the continuity of the logistics pathway. Where the evidence is insufficient to establish whether a stage can sustain redirected flows, the assessment records this limitation rather than assuming that the relevant requirement is satisfied. The framework does not impose a composite score or predefined numerical thresholds; instead, it uses the available quantitative indicators and qualitative evidence to support a structured, port-specific diagnostic assessment. Beyond the port, the assessment follows two possible functional pathways according to the role performed by the port within the adapted network. For gateway flows, the sequence continues through hinterland accessibility, logistics capability and market connectivity. Hinterland accessibility evaluates the availability and capacity of road, rail and intermodal connections; logistics capability considers the infrastructure and services required to store, consolidate, transfer and redistribute cargo; and market connectivity assesses the ability of the resulting configuration to connect cargo efficiently with relevant inland production and consumption areas [2,21,25].

For transhipment flows, the post-port sequence is different. The assessment considers terminal transfer capability and onward maritime connectivity, including the availability of connecting services and the port's integration within feeder and deep-sea networks [23]. In this configuration, the continuity of redirected flows depends less immediately on inland transport capacity and more strongly on whether cargo can be transferred efficiently between maritime services and continue towards subsequent ports and destinations. Ports combining gateway and transhipment functions may therefore require both pathways to be assessed [24]. This distinction is well established in the literature on container shipping networks, where gateway traffic is associated with hinterland-generated flows whereas transhipment involves ship-to-ship redistribution and may coexist with gateway functions within the same port [24].

The PR-SST establishes a sequential rather than compensatory logic, which is applied through the PR-SA. Strong performance in one dimension does not offset a critical constraint at another stage of the logistics chain. A port with substantial terminal capacity, for example, cannot constitute an effective substitute if redirected gateway cargo cannot be accommodated by its hinterland connections or if transhipment cargo lacks sufficient onward maritime connectivity [9,23,25]. Effective substitutability is consequently

determined by the ability of the entire relevant pathway to sustain redirected flows, while the stage at which a significant constraint emerges identifies a potential source of post-rerouting dependency.

Sustainability is incorporated as a cross-cutting dimension rather than as an additional sequential stage. Changes in sailing distance, inland transport distance, modal configuration, congestion, transport costs and associated emissions are considered across the relevant pathway [13,16,17]. This makes it possible to distinguish between an adaptive configuration that merely preserves cargo movement and one that does so without generating disproportionate environmental or operational pressures elsewhere in the transport system.

3.3. Assessment Procedure and Indicators

The PR-SA operationalises the PR-SST through a set of indicators corresponding to the sequential dimensions defined in Section 3.2. Indicator selection reflects the multidimensional nature of port and logistics resilience, combining maritime connectivity, port operational capacity and the ability of the wider transport network to accommodate and redistribute cargo flows [7,9]. Rather than assessing these components independently, the procedure follows the movement of redirected cargo across the relevant logistics pathway, allowing constraints emerging at different stages of the adapted configuration to be identified and assessed.

The implementation of the PR-SA follows three steps. First, indicators are selected according to their relevance to the continuity of logistics pathways, their availability across the case-study ports, and their comparability over the observation period. This indicator-based approach is consistent with previous research on port–hinterland transport network resilience and maritime logistics resilience [9,10]. The selected indicators cover port traffic, maritime connectivity, terminal operations, and hinterland access, as applicable to the function performed by each port. Second, each port is assessed in terms of effective substitutability and post-rerouting dependency. Effective substitutability is examined by determining whether the alternative port and its associated logistics connections can accommodate redirected flows and sustain their onward movement, reflecting the importance of network connectivity, redundancy, and adaptive capacity in maritime transport resilience [9,29]. Post-rerouting dependency is assessed by identifying whether the rerouted pathway creates or reinforces reliance on specific services, terminals, transport connections, or operational arrangements. Third, potential binding constraints are identified by examining the stages of the pathway where quantitative indicators or documentary evidence reveal limitations that may impede flow continuity. A potential binding constraint is identified when the available evidence indicates that a limitation at a given stage may restrict the effective use of the alternative pathway, even if other stages retain sufficient capacity or connectivity. The assessment is therefore sequential and non-compensatory: favourable conditions at one stage do not automatically offset a critical limitation at another. This constitutes an operational principle of the PR-SST rather than an assumption that overall resilience can be inferred from the performance of individual components. Where evidence is incomplete or indicators are not comparable, the assessment records this limitation rather than inferring values or assigning unsupported scores.

The assessment begins by characterizing each port's functional profile, particularly the relative importance of gateway and transhipment activities [24]. Two common dimensions are then examined across all case-study ports: maritime connectivity and port capacity. Maritime connectivity is assessed through indicators describing each port's position and connections within liner shipping networks, while port capacity is examined using available evidence on container throughput, terminal capacity, and operational conditions [7,8,26]. These dimensions provide the basis for assessing whether redirected flows

can reach and be accommodated by an alternative port. The subsequent assessment is function-specific, reflecting the different logistics pathways associated with gateway and transhipment activities. The subsequent assessment depends on the function performed by the port within the reconfigured logistics network. For gateway-oriented flows, the analysis considers hinterland accessibility, logistics capability and market connectivity. Indicators relating to road and rail accessibility, intermodal connections, inland terminals and logistics infrastructure are used to assess whether additional cargo can be transferred efficiently from the maritime gateway towards inland destinations [2,9,21,25]. The assessment of gateway pathways is subject to limitations in the availability and comparability of data on inland transport infrastructure. Although road accessibility, rail connections, intermodal facilities, and hinterland logistics are relevant to the continuity of port–hinterland flows, the available evidence does not support a systematic, comparable measurement of their operational capacity or potential constraints across all case-study ports. Accordingly, the gateway pathway assessment identifies relevant logistical dependencies but should not be interpreted as a comprehensive evaluation of inland transport capacity. For transhipment-oriented flows, the analysis focuses on terminal transfer capability and onward maritime connectivity, including the availability of connecting maritime services and the port's integration within feeder and deep-sea networks [24]. Where gateway and transhipment functions coexist, both pathways are examined.

The operational structure of the PR-SST is presented in Figure 1. The framework combines the two common assessment dimensions with function-specific gateway and transhipment pathways. Sustainability is incorporated as a cross-cutting dimension across both pathways, while the final diagnostic stage integrates the evidence to assess effective substitutability and identify post-rerouting dependencies.

While the PR-SST conceptually accommodates the assessment of environmental and sustainability-related implications across these pathways, the present PR-SA application addresses this dimension qualitatively, as comparable environmental indicators are not consistently available for the five selected ports.

The indicators are not aggregated into a composite index or overall port score. Instead, the PR-SA applies the sequential diagnostic approach established by the PR-SST, examining evidence across successive stages of the relevant pathway. This makes it possible to identify the point at which the capacity to accommodate or redistribute redirected flows becomes constrained. Strong performance at one stage is therefore not assumed to compensate for a critical limitation elsewhere in the logistics configuration. The analytical emphasis is placed on the identification of binding constraints and post-rerouting dependencies, rather than on the comparative ranking of ports [9,23,25].

For operational purposes, effective substitutability is assessed through three criteria: (i) the availability of maritime connectivity and sufficient port and terminal capacity to receive redirected flows; (ii) the adequacy of the subsequent logistics pathway, assessed through hinterland accessibility, logistics capability and market connectivity for gateway flows, or terminal transfer capability and onward maritime connectivity for transhipment flows; and (iii) the continuity of cargo movement across the relevant pathway. A stage is identified as a potential binding constraint when quantitative indicators or documentary evidence suggest that limitations in capacity, connectivity or operational capability may prevent or materially restrict the onward movement of cargo. A dependency is identified when the continuity of cargo movement relies on specific ports, maritime services, terminals, inland corridors or logistics nodes. Where comparable evidence before and after rerouting is available, changes in these dependencies are assessed as increased, decreased or broadly unchanged; where such evidence is unavailable, only structural dependencies are identified, without inferring temporal change. The assessment follows a sequential and non-compensatory logic: a critical constraint at one stage cannot be offset by adequate

performance at another. The indicators are not aggregated into a composite score, and no overall port ranking is produced. Where comparable temporal data are available, indicators are examined in relation to conditions before and after the onset of rerouting in order to identify changes in traffic patterns, capacity utilisation, connectivity or logistics pressure. The analysis does not attribute every observed change exclusively to the disruption; rather, temporal comparison is used together with documentary and contextual evidence to assess whether changes are consistent with the reconfiguration of maritime and logistics flows. This approach reduces the risk of interpreting coincident changes as direct effects of rerouting.

The observed changes are not attributed exclusively to Red Sea rerouting. Variations in port throughput, maritime services and connectivity may also reflect changes in market demand, shipping network strategies and other operational developments. Accordingly, the 2023–2024 comparison is used to contextualise changes occurring during the disruption period, rather than to isolate its causal effect. Developments explicitly linked to the disruption in the documentary sources are distinguished from general changes in port activity, and the findings are interpreted as evidence consistent with rerouting-related adjustments rather than as definitive proof of causality. The evidence examined through the PR-SA is interpreted according to three interrelated elements: flow continuity, binding constraints and dependency reconfiguration. Flow continuity reflects the ability of the adapted configuration to maintain cargo movement across the relevant pathway, while binding constraints identify the stage at which limited capacity, connectivity or operational capability restricts that movement [9,23,25]. Dependency reconfiguration captures situations in which rerouting increases reliance on particular ports, onward maritime services, inland corridors or logistics nodes, even when cargo continuity is preserved [7,19]. Sustainability evidence is considered alongside these operational dimensions to determine whether adaptation is associated with additional transport distances, congestion, costs or emissions [13,16,17]. The resulting interpretation therefore distinguishes between configurations that effectively absorb redirected flows and those in which continuity is maintained at the expense of new constraints, dependencies or sustainability pressures.

The empirical assessment draws on three categories of evidence: (i) official port traffic statistics, including container throughput, total cargo handled and vessel calls; (ii) maritime connectivity evidence, including liner services, port calls and changes in service configurations; and (iii) documentary evidence on terminal operations, hinterland connections and reported disruption-related pressures. For Algeciras, Valencia and Barcelona, traffic data are obtained from the annual statistical reports published by Puertos del Estado and the respective port authorities [30–36]. For Rotterdam, data are obtained from the Port of Rotterdam Authority [34], while for Sines, the corresponding source is the Administração dos Portos de Sines e do Algarve [35,36]. Eurostat maritime transport statistics are used, where applicable, to support cross-port comparisons based on harmonised definitions [37].

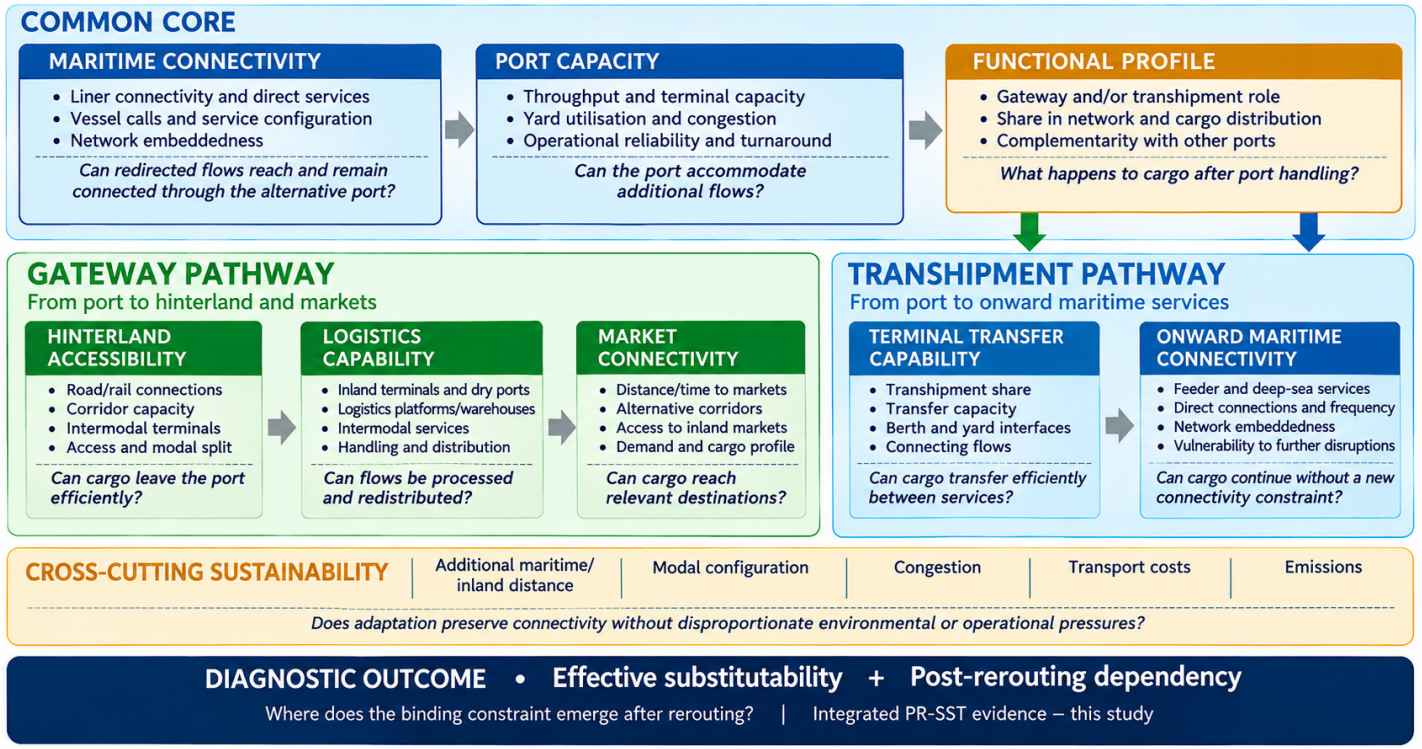


Figure 1. Conceptual structure of the Post-Rerouting Sequential Stress Test (PR-SST), distinguishing common maritime–port conditions from function-specific gateway and transhipment pathways and incorporating sustainability as a cross-cutting dimension. The grey arrows indicate the sequential progression of the assessment, while the green and blue arrows distinguish the gateway and transhipment pathways, respectively. The framework draws on previous studies addressing maritime connectivity [6,7,20], port capacity [11,18,24], functional port profiles [21,23], hinterland accessibility [2,22,25], logistics capability [14,15,22], market connectivity [13,22,25], terminal transfer capability [23,24], onward maritime connectivity [18,20,23], and cross-cutting sustainability considerations [11,13,15–17,24].

Gateway and transhipment activities represent distinct port functions and are considered in the interpretation of each case. Rather than quantifying the relative contribution of these activities to total port traffic, the assessment documents the functional orientation of each port using the available port authority reports and other relevant documentary evidence. This characterisation informs the selection and interpretation of the pathway-specific requirements examined under the PR-SST. For gateway-oriented flows, particular attention is given to hinterland accessibility, logistics capability, and connections to inland destinations. For transhipment-oriented flows, the assessment focuses on terminal transfer requirements, feeder services, and onward maritime connectivity. Where gateway and transhipment functions coexist, both pathways are considered. This approach makes the functional differences between the case-study ports explicit without treating aggregate traffic volumes as a direct measure of functional substitutability.

Annual container throughput is used in this study to characterize port activity and examine changes in traffic patterns following maritime rerouting; it is not interpreted as a direct measure of available port capacity. The objective of the PR-SST is to assess the substitutability of port–hinterland pathways and identify dependencies and potential constraints affecting the continuity of redirected flows, rather than to estimate spare capacity or quantify congestion. Accordingly, conclusions concerning port substitutability are based on the combined interpretation of traffic data, maritime connectivity, and available documentary evidence on terminal operations and hinterland access. A detailed assessment of capacity utilization, congestion, and terminal-level operational constraints would require more granular operational data and falls outside the scope of the present study.

The observation period covers 2023–2024, using 2023 as the reference year and 2024 as the first full calendar year affected by the Red Sea disruption [18,20]. The indicators considered include container throughput, expressed in twenty-foot equivalent units (TEU); total cargo handled, expressed in tonnes; and vessel calls, where reported by the respective sources. Additional evidence on maritime connectivity and operational conditions is recorded for the specific dates or periods reported in the original sources [21,24,30–36]. For each observation, the indicator, reported value, unit, reference period, source and relevant methodological qualifications are recorded. The 2023–2024 traffic statistics are used to contextualise changes in port activity and are interpreted alongside documentary evidence on maritime connectivity, service configurations and operational conditions. Annual variations are not treated as direct measurements of rerouted cargo flows or as proof of causality. The evidence is subsequently organised by port and mapped onto the relevant PR-SA pathway, distinguishing gateway and transhipment requirements. Where comparable quantitative evidence is unavailable, the corresponding limitation is recorded and the assessment relies on the available documentary evidence without inferring missing values or assigning composite scores.

4. Results

The results are presented through the application of the Post-Rerouting Sequential Assessment (PR-SA), following the analytical structure established by the PR-SST. The assessment examines the available evidence for each port across the relevant sequential dimensions, distinguishing gateway and transhipment pathways. The findings identify documented operational conditions, potential constraints and emerging dependencies, while explicitly recognising limitations in the availability and comparability of the underlying evidence.

4.1. Port Profiles and PR-SA Assessment

The Red Sea crisis altered established Asia–Europe shipping patterns, redirecting services around the Cape of Good Hope and producing heterogeneous effects across

European ports [18,20]. Changes in maritime service configurations following the onset of the Red Sea crisis were documented by the European Commission, including the addition of Western Mediterranean ports, such as Sines, Valencia and Barcelona, to Far East and Middle East connections. These changes were considered largely related to the Red Sea situation [38]. Operational evidence published by Maersk in June 2024 additionally reported increased waiting times and yard density at Barcelona, as well as delays in vessel arrivals, long layovers and imbalances in yard density at Algeciras [39]. These observations demonstrate that the disruption was associated with changes in shipping-service configurations and port operating conditions, although the nature and magnitude of the effects differed between ports. They do not, however, establish a uniform increase in cargo volumes across all five cases. Accordingly, the PR-SA distinguishes documented changes in services and operations from inferred changes in cargo flows and assesses the implications of rerouting in light of the evidence available for each port. The five ports selected for the application of the PR-SA—Algeciras, Valencia, Barcelona, Rotterdam and Sines—represent contrasting logistics configurations for examining the implications of maritime rerouting. Algeciras, Valencia, Barcelona and Rotterdam differ in geographical position, maritime connectivity and hinterland integration, while available evidence from the Red Sea crisis indicates heterogeneous operational pressures and resilience responses across these ports [7,18]. In particular, the port-level analysis conducted by Liu et al. [7] identified Algeciras as displaying relatively low congestion and rapid recovery, whereas Barcelona experienced a comparatively less favourable resilience response; Rotterdam and Valencia were also included in the 20-port empirical assessment. The reported increases in waiting times and yard density at Barcelona [33], together with its comparatively less favourable resilience response [7], indicate operational pressures during the disruption period. However, these observations do not demonstrate that the port was unable to accommodate redirected flows or that specific gateway or transhipment pathways failed. Within the PR-SA, they are therefore interpreted as evidence of operational pressure and indicators of potential constraints on effective substitutability, rather than as confirmation of a binding operational limitation.

The selection of the five ports follows a purposive comparative logic rather than an attempt to achieve geographical representativeness. The concentration of four cases in the Iberian Peninsula—Algeciras, Valencia, Barcelona and Sines—allows the analysis to examine differences in maritime network position, port functions and hinterland integration within the same broad geographical region. This regional focus is particularly relevant for investigating whether proximity within a shared regional context necessarily translates into effective substitutability, or whether differences in gateway and transhipment functions generate distinct constraints and dependencies. Rotterdam provides a contrasting Northern European case, introducing a different geographical and hinterland context against which the analytical value of the PR-SST can be further examined.

Sines provides an additional configuration of particular relevance to the present analysis because of its role as a container hub combining maritime connectivity with transhipment and access to the Iberian hinterland. Container throughput reached approximately 1.9 million TEU in 2024, 16% above 2023, while five new regular services were added to its connectivity network. At the same time, ongoing rail improvements are intended to strengthen access to the Spanish market and expand the port's penetration into the Iberian hinterland [35,36]. While the reported increase in container throughput and the addition of regular maritime services are documented developments, the implications of ongoing rail improvements for effective gateway substitutability remain prospective. The available evidence does not establish the additional inland transport capacity that could be mobilised to accommodate redirected flows or demonstrate the existence of a binding hinterland constraint. Within the PR-SA, hinterland connectivity is therefore considered a

potential source of dependency rather than an empirically confirmed operational bottleneck. These characteristics make Sines particularly relevant for examining the interaction between transhipment and gateway functions within the same post-rerouting logistics configuration.

The selected cases therefore represent different combinations of maritime connectivity, port capacity and post-port logistics functions. The PR-SA is applied comparatively to determine whether these differences influence the ability of each configuration to accommodate and redistribute redirected flows and, critically, where constraints and dependencies emerge along the gateway or transhipment pathway. Table 2 presents a comparative overview of the selected ports, integrating their functional profiles, documented operational evidence, and the potential constraints and dependencies identified through the PR-SA. The subsequent analysis discusses the main implications of these findings for effective substitutability and post-rerouting dependency across gateway and transhipment pathways.

The comparative assessment also highlights the limits of the available evidence for evaluating the sustainability implications of post-rerouting adjustments. Increased waiting times and yard density at Barcelona indicate potential operational inefficiencies, while rail improvements at Sines may strengthen hinterland connectivity. Nevertheless, these observations cannot be interpreted as direct measurements of environmental performance. Across the five ports, comparable data on additional maritime and inland transport distances, modal shares, transport costs and emissions are not consistently available. Consequently, although sustainability is incorporated into the PR-SST as a cross-cutting conceptual dimension, its application through the PR-SA remains qualitative and does not support a quantitative comparison or ranking of the ports in terms of sustainability performance.

Table 2. Comparative application of the PR-SA to the selected European ports.

Port	Evidence During Rerouting Period		Functional Profile and Pathway		Post-Rerouting Dependency/Diagnostic Focus	Sustainability Evidence and Limitation
	Traffic and Operational Evidence	Sources	Role(s)	Pathway and Rationale		
Algeciras	• 4.71 million TEU in 2024. • Reduced container traffic during the rerouting period.	[30]	Transhipment gateway; also gateway to the Iberian hinterland.	Common core → Transhipment + Gateway. Leading Mediterranean transhipment hub with a gateway function.	• Connectivity supports the transhipment role; hinterland access matters for gateway flows. • Available evidence does not quantify spare capacity or establish the scale of rerouted cargo.	No comparable port-specific figures are reported for transport distance, modal split, costs or emissions. Sustainability implications cannot be quantified or ranked across cases.
Valencia	• Transhipment containers increased by 13.08% year-on-year in May 2024. • Changes in Asia–Europe services were documented.	[31,32]	Gateway and transhipment port.	Common core → Gateway + Transhipment. Relevant Spanish gateway with significant transhipment activity.	• Both pathways are relevant. • The May monthly increase does not establish the amount of rerouted cargo or demonstrate the absence of capacity constraints.	The evidence used here does not provide comparable port-level transport-distance, modal-share, cost or emissions measures. No quantitative sustainability comparison is possible.
Barcelona	• 3.90 million TEU in 2024 (+19%). • Growth associated with transhipment and containerised traffic. • Operational reports noted increased waiting times and yard density during the disruption.	[33,39]	Gateway and transhipment port.	Common core → Gateway + Transhipment. Diversified traffic structure and strong hinterland connectivity.	• Higher throughput alone does not establish effective substitutability. • Reported waiting times and yard density indicate operational pressure to consider alongside hinterland access.	Operational pressure is documented qualitatively, but comparable congestion, inland-mode, distance, cost and emissions data are not available in the evidence assembled. Environmental effects cannot be quantified.
Rotterdam	• 13.78 million TEU in 2024 (+2.6%). • Rerouting involved longer vessel rotations and changes to shipping schedules.	[34]	Gateway and transhipment hub.	Common core → Gateway + Transhipment. Major European hinterland gateway and key North-West European transhipment hub.	• Both pathways are relevant. • Longer rotations may affect service configuration, but the available evidence does not	No harmonised case-level data are reported for additional transport distance, modal configuration, costs or emissions. A comparative

					isolate rerouting-related capacity or congestion effects.	sustainability ranking would be unsupported.
Sines	• 1.90 million TEU in 2024 (+16%). • Five new regular services. • Rail improvements intended to strengthen access to the Spanish market and Iberian hinterland.	[35,36]	Transhipment hub with a developing gateway function.	Common core → Transhipment + Gateway. Atlantic transhipment hub with high• expanding connectivity and developing hinterland access.	• New services indicate expanded maritime connectivity. Rail improvements may support gateway potential, but their realised effect on inland flows is not quantified.	Rail development is documented qualitatively, but comparable modal-share, distance, cost and emissions figures are not reported. Its sustainability effect cannot be quantified against the other ports.

Note: TEU = twenty-foot equivalent unit; PR-SA = Post-Rerouting Sequential Assessment. Traffic and operational evidence relate to the 2024 rerouting period. The assessment is based on publicly available port statistics and documentary evidence. The reported traffic figures do not represent available spare capacity, and the absence of harmonised sustainability data prevents a quantitative comparison across ports.

4.2. Effective Substitutability and Post-Rerouting Dependencies

The comparative application of the PR-SA, structured by the PR-SST, reveals differences in the logistics requirements and potential dependencies associated with the five port configurations. These differences are not explained by port capacity or maritime connectivity alone, but also by the functional role of each port and the subsequent pathway through which cargo must continue [7,18]. The assessment therefore distinguishes between evidence supporting the continuity of redirected flows, potential constraints at successive logistics stages, and dimensions for which the available data remain insufficient to establish effective substitutability. For gateway-oriented flows, effective substitutability depends increasingly on the capacity of the hinterland system to absorb and redistribute additional cargo. Rail and road accessibility, intermodal connections and inland logistics capacity therefore become potential binding constraints once maritime and terminal capacity have been secured [2,9,22,25]. In this configuration, an alternative port may provide sufficient handling capacity while the resulting logistics chain becomes more dependent on specific inland corridors or transport modes. The constraint is consequently displaced from the maritime or terminal stage towards the port–hinterland interface.

For transhipment-oriented flows, the dependency structure is different. Cargo continuity depends primarily on terminal transfer capability and the availability of onward maritime services [23]. The ability to receive additional vessels or containers is therefore insufficient if connecting services, terminal interfaces or subsequent maritime links cannot accommodate the redistributed traffic. In mixed ports, both pathways may operate simultaneously, meaning that the same rerouting episode can generate different dependencies according to the subsequent destination and function of the redirected cargo.

The comparison therefore supports a distinction between nominal capacity and effective substitutability. The existence of available capacity at an alternative port represents only the first condition of substitution; effective substitutability depends on the continuity of the relevant post-port pathway. Rerouting may consequently preserve maritime connectivity while increasing reliance on particular maritime services, terminals, inland corridors or logistics nodes. These post-rerouting dependencies do not necessarily imply failure of the adaptive response, but they reveal where the reconfigured system may become increasingly constrained or exposed.

Sustainability further qualifies this assessment. Longer maritime or inland distances, changes in modal configuration, congestion and additional transport requirements may allow cargo continuity to be maintained while increasing costs, emissions or infrastructure pressure [13,16,17]. An alternative logistics configuration can therefore be operationally effective without necessarily representing the most sustainable adaptation. Effective substitutability should consequently be assessed not only by whether redirected flows continue to move, but also by the dependencies and sustainability pressures generated by the resulting configuration.

5. Discussion

5.1. Theoretical and Methodological Implications

The findings extend existing research on maritime and port resilience, which has emphasised redundancy, network connectivity, alternative routing and recovery capacity [7,18,19], by shifting the analytical focus towards the continuity of logistics pathways following rerouting. The contribution of the PR-SST and its operational application through the PR-SA lies in connecting network-level adaptation with the sequential requirements of gateway and transhipment pathways, including terminal operations, onward maritime connectivity and hinterland accessibility. This approach enables the identification of

potential constraints and emerging dependencies beyond the preservation of maritime connectivity.

The empirical evidence, including changes in port traffic, maritime connectivity and service configurations, illustrates how ports and maritime networks responded to rerouting but does not, in itself, demonstrate effective substitutability or overall resilience. These concepts are assessed through the successive stages of the PR-SST, operationalised by the PR-SA, while recognising that the available data may not establish the full operational effectiveness of the resulting logistics configurations. A central implication is the distinction between nominal capacity and effective substitutability. Although previous research has highlighted the importance of port capacity, connectivity and hinterland accessibility for port and supply-chain resilience [2,7,9,21,23,25], the present analysis demonstrates the need to assess these dimensions sequentially. Sufficient terminal capacity and maritime connectivity do not necessarily ensure effective substitutability if constraints arise in inland corridors, intermodal facilities or onward maritime services. Effective substitutability should therefore be understood as a system-level, function-dependent property of the reconfigured logistics pathway rather than an intrinsic characteristic of an alternative port.

5.2. Gateway and Transhipment Pathways and Post-Rerouting Dependencies

The distinction between gateway and transhipment functions further qualifies this interpretation. Much of the discussion surrounding port resilience implicitly assumes that additional cargo reaching an alternative port must subsequently be absorbed by its hinterland. However, the cases examined here show that redirected flows may follow fundamentally different post-port pathways. Gateway cargo transfers pressure towards road, rail, intermodal and inland logistics systems, whereas transhipment cargo remains dependent primarily on terminal transfer capability and onward maritime connectivity [23]. Ports combining both functions may therefore experience simultaneous but different forms of stress. This distinction is particularly relevant for ports such as Sines, where transhipment activity coexists with ambitions to strengthen access to the Iberian hinterland. The resilience implications of additional traffic consequently depend not only on how much cargo reaches a port, but on what happens to that cargo afterwards.

This perspective also provides a basis for interpreting post-rerouting dependency. Adaptation can maintain cargo continuity while altering the nodes, corridors and services on which the transport system depends. Such dependency reconfiguration should not automatically be interpreted as a failure of resilience: it may be the mechanism through which continuity is achieved. However, increasing reliance on a particular inland corridor, terminal interface, feeder connection or alternative maritime service may create new concentration points within the adapted network. This complements existing evidence that maritime disruptions can redistribute traffic and alter network centrality and port exposure [7,18,19], while extending the analysis beyond the immediate maritime response. The key resilience question is therefore not only whether the original disruption has been bypassed, but also where dependencies emerge following adaptation.

5.3. Sustainability and Practical Implications

The findings also reinforce the need to consider resilience and sustainability jointly. Rerouting can preserve supply-chain continuity while increasing sailing distances, inland transport requirements, congestion, costs and emissions [13,16,17]. Conversely, an operationally effective alternative may become more sustainable where redirected flows can be absorbed through efficient rail or intermodal connections rather than through additional road transport. Resilience and sustainability should therefore not be assumed to evolve in parallel. This is consistent with emerging literature calling for resilience indicators to be integrated with environmental and cost considerations in port–hinterland assessment [2].

The PR-SST contributes to this integration by treating sustainability as a cross-cutting property of the adapted pathway rather than as an independent outcome considered after resilience has been assessed.

The practical implications of the PR-SST and PR-SA concern both infrastructure investment and contingency planning. For port authorities and infrastructure managers, the assessment can help identify the stage at which constraints are most likely to limit the effective use of redirected flows, thereby supporting the prioritisation of investments in terminal handling capacity, intermodal facilities, rail connections or access corridors, depending on the constraint identified and possible adaptation. For gateway ports, this may involve assessing whether road and rail infrastructure can accommodate additional inland movements; for transhipment-oriented operations, priorities may include terminal transfer capacity and the availability of onward maritime connections. For logistics operators, PR-SST results can inform contingency plans by identifying alternative port and route combinations, critical transfer points and dependencies on specific terminals, inland corridors or feeder services. Operators can use this information to prepare alternative routing arrangements and assess where additional capacity or coordination may be required if disruption persists. The framework can therefore support more targeted investment and contingency planning by linking decisions to the specific constraints and dependencies identified along the logistics pathway, rather than relying solely on the availability of alternative ports or aggregate terminal capacity. Although sustainability is incorporated as a cross-cutting dimension of the PR-SST and PR-SA frameworks, its empirical assessment in this study is limited by the availability of comparable data on emissions, transport distances, modal shifts and logistics costs across the selected ports and pathways. Accordingly, the analysis does not provide a comprehensive quantitative assessment of the environmental and economic implications of rerouting. Sustainability is retained as a relevant dimension for interpreting logistics reconfiguration, while a more systematic evaluation would require additional data on transport operations and their associated environmental and economic impacts.

5.4. Limitations and Future Research

Several limitations should be considered when interpreting the comparative findings. First, the availability and comparability of port-level data vary across indicators and locations, restricting the extent to which observed differences can be assessed using fully consistent measures. Second, changes in port traffic and maritime connectivity may reflect factors beyond rerouting, including seasonal variation, changes in shipping services and broader market conditions. Although the analysis considers temporal patterns and complementary documentary evidence where available, these factors cannot always be isolated empirically. Consequently, the findings should be interpreted as evidence of patterns consistent with maritime rerouting and of the constraints affecting the continuity of logistics pathways, rather than as definitive causal estimates of its effects.

6. Conclusions

Maritime rerouting is a fundamental adaptive response to disruptions affecting global shipping networks, but maintaining cargo movement does not necessarily mean that the resulting logistics configuration is equally resilient or sustainable. The study contributes to this debate through three interrelated concepts. First, it distinguishes nominal capacity from effective substitutability, conceptualizing the latter as a system-level and function-dependent property of the post-rerouting logistics configuration. Second, it introduces post-rerouting dependency to identify how adaptation can preserve continuity while increasing reliance on particular ports, inland corridors, intermodal facilities or onward maritime services. Third, the Post-Rerouting Sequential Stress Test (PR-SST)

provides a structured framework for examining these issues across gateway and transhipment pathways, with sustainability incorporated as a cross-cutting analytical dimension. The comparative assessment documents changes in port traffic, maritime service configurations, and selected operational conditions following the Red Sea disruption. However, the potential logistics constraints and post-rerouting dependencies identified through the PR-SA should be interpreted as diagnostic findings rather than as directly quantified operational limitations, given the absence of harmonised data on spare capacity, terminal-level performance, and sustainability outcomes.

The analysis has practical implications for port and transport planning. Contingency planning should assess not only the availability of alternative ports and terminal capacity, but also the operational continuity of the logistics pathways required to accommodate redirected flows. For gateway activities, this entails examining the capacity of hinterland connections and associated logistics infrastructure to accommodate additional traffic. For transhipment activities, it requires attention to terminal transfer operations and the availability of onward maritime connections. Infrastructure investment and disruption preparedness should therefore consider potential constraints across the adapted logistics configuration rather than treating additional capacity at an individual port as sufficient evidence of improved system resilience. The PR-SST and PR-SA can support this assessment by identifying documented operational conditions and potential bottlenecks, rather than by providing a definitive quantitative measure of resilience. The conclusions should be interpreted in light of the study's comparative case-study design and its reliance on secondary data, whose availability and comparability vary across ports and analytical dimensions. Future research should therefore apply the PR-SST and PR-SA to additional disruption episodes and port systems and further develop quantitative indicators capable of measuring capacity buffers, dependency concentration and environmental consequences across post-rerouting pathways. Such applications would allow the framework to be tested under different network configurations and contribute to a more integrated assessment of resilience and sustainability in maritime logistics.

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