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Redundancies of African port hinterlands and their implications for new container port investments

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ABSTRACT

Improving connectivity between ports and the hinterlands they serve is critical for reliable and cost-efficient freight transport. However, overreliance on a single port, or small subset of ports, can cause economic losses when those ports fail, given limited redundancies of port-hinterland systems. However, planners often lack critical insights into port-hinterland redundancy. Here, we analyse the port-hinterland redundancies across Africa, a continent with a small number of gateway ports serving large hinterlands and large investment need in the coming decades, providing a window of opportunity to embed redundancy in strategic transport investments. We find that regions with high accessibility, in particular coastal cities close to a major seaport (e.g., Namibia, Senegal, Kenya) have low redundancy. In contrast, some landlocked hinterlands (e.g., Zambia, Zimbabwe, Niger, and Chad) have low accessibility, yet high redundancies given their reliance on different port ranges. We further show that new transport investments aimed at improving accessibility can create both synergies and trade-offs with system redundancy. Port terminal expansions, in particular, can reduce the redundancy of the core hinterland while improving the redundancy of the hinterland periphery. Rail connections can improve access to a wider set of ports at a comparable cost but can also reinforce the dependency on a single cost-efficient rail connection. Analysing redundancies of port hinterlands can support strategic planning of regional investments and help improve the resilience of the regional and continental transport system against disruptions.

1. Introduction

Ports are key in connecting regions of economic activity across borders, thereby facilitating the movement of cargo flows (Notteboom and Rodrigue, 2008; Verschuur et al., 2022a). It has been shown that access to modern, well-connected ports can drive economic development (Fugazza and Hoffmann, 2017; Limão and Venables, 2001; Rojon et al., 2021; Wilmsmeier and Martínez-Zarzoso, 2010). For instance, improving port efficiency can help bring transport costs down, which in turn boosts international trade (Limão and Venables, 2001). Moreover, a doubling of a country's central position in maritime transport can lower transport costs with 16% (Wilmsmeier and Martínez-Zarzoso, 2010). Therefore, investing in port capacity, hinterland connectivity and port efficiency is central in driving down trade cost, which are still a barrier to trade in many countries, in particular in Africa (Raballand et al., 2012).

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Transport planning is traditionally focused on improving the accessibility between ports and their hinterlands (e.g., investment in transport corridors), through expanding or modernizing ports and improving hinterland accessibility. Within the transport literature, the port-hinterland concept is usually researched through the lens of port choice, which captures the key factors that determine shippers' decisions on choosing certain ports over others (Haralambides et al., 2011; Magala and Sammons, 2015; Mueller et al., 2020; Veldman and Bückmann, 2003; Zondag et al., 2010). Transport investments are then targeted to increase the port's market share and improve the economic efficiency of the port-hinterland transport system. For instance, Zondag et al. (2010) analysed the port choice across the European hinterland to evaluate the impact of various transport policies (e.g., change in hinterland transport cost, improving port efficiency). Haralambides et al. (2011) studied the most promising location of a new port in the Nairobi-Durban port range by analysing the market share it could capture in the East African hinterland.

The aforementioned tendency to focus on economic efficiency alone may come at the expense of reduced resilience of port-hinterland freight flows, which reflect the ability of the transport system to cope, recover, and adapt to external disturbances such as labour strikes, geopolitical conflict, extreme weather events or mechanical failure (Verschuur et al., 2022b). Transport resilience is generally considered to be determined by four factors, as proposed by the "4R" resilience framework: robustness, redundancy, resourcefulness, and rapidity (Bruneau et al., 2003; Tierney and Bruneau, 2007). Out of the different resilience dimensions, most relevant for the port-hinterland context is the redundancy of the system, that is, the ability of the system to buffer disruptions to one or multiple ports by rerouting goods to other ports or routes in the network. Recently, some research has emerged on quantifying redundancies of national road transport systems (Koks et al., 2023) and maritime shipping networks (Xu et al., 2024). However, the concept of transport redundancy, or transport resilience more broadly, is rarely applied on a port-hinterland scale (Verschuur et al., 2022b), which requires taking a system-wide approach of the port and hinterland transport system in conjunction. Taking the port-hinterland scale also allows for an exploration how the concept of redundancy can be contextualised within framework of port choice modelling. While the concepts of port choice and port-hinterland redundancy are intrinsically linked, as redundancy is governed by the set of ports it depends on, no research till date has explored this link.

Understanding port-hinterland redundancies is increasingly important given the volatility of maritime shipping and port operations, which are frequently affected by external disturbances. These disturbances, if long-lasting, can affect entire port hinterlands, in particular if rerouting options are not available, lack capacity, or are prohibitively expensive (Verschuur et al., 2022b, 2020; Xu et al., 2024).

While investigating port-hinterland redundancies is relevant across geographical settings, it is particularly important within the African port context, for several reasons. Firstly, the number of major gateway ports is relatively limited, and these gateway ports serve large hinterlands (Haralambides et al., 2011). Hence, these hinterlands tend to have limited redundancies, reinforced by strong trade frictions that exist within Africa (e.g., higher border compliance costs). Secondly, demand for port capacity across the continent is surging, far exceeding existing spare port capacity (ITF, 2015; World Bank, 2018). At the same time, many African ports are still struggling with inefficiencies and congestion (Onwuegbuchunam, 2013; Raballand et al., 2012). Hence, major port and hinterland transport expansion and improvement projects are currently being planned, providing a window of opportunity to target new developments to improve both hinterland accessibility and redundancy. Thirdly, African ports are facing a variety of risks that can cause disruptions to port operations, such as labour strikes (e.g., the 2022 labour strike of South Africa's rail and port workers), extreme weather events (e.g., 2023 Durban floods, 2023 port closures in Egypt due to strong winds and waves), and geopolitical or local conflict (e.g., 2024–2024 Houthi rebels attacks affecting the Red Sea, 2023 conflict in Sudan affecting its maritime operations). As such, evaluating port-hinterland accessibility and redundancy is key for strategic planning and improving the resilience of the continent's transport network. This can help ensure that the development gains of efficient transport systems are to be realised.

In this paper, we quantify the redundancy of African port hinterlands in case of port disruptions. We focus on container ports, given that their investment needs are largest among terminal types (World Bank, 2018), hinterland competition is more fierce (especially for transshipment ports), and goods can be easily substituted via alternative container ports. We construct an accessibility and redundancy metric per administrative area in Africa (780 subnational units) and compare and contrast the two per subnational unit. In addition, we showcase how investments in new greenfield ports, terminal expansions, and railway investments can affect the redundancy of port hinterlands. This information can readily feed into regional port planning strategies as well as allowing the quantification of the economic impacts (e.g., due to transport rerouting, delays, supply disruptions) of port disruptions.

The paper continues with a literature review covering research on port hinterlands and transport resilience. This is followed by a description of the methodology employed and a section with the main results. We close with a discussion of the results, and a plea for further analyses to support the improvement of transport resilience against a variety of disturbances.

2. Literature review

We discuss two lines of previous research, which we consider relevant for the framing of our study. These include the transport resilience literature, with a particular focus on maritime and land-based transport networks, and the port choice literature, which covers the choice preferences and accessibility aspects of ports and their respective hinterlands. This is followed by an overview of three research gaps we have identified and subsequently address in this study.

2.1. Transport resilience

The resilience of a transport system, whether maritime, air, road, rail or intermodal, is defined as its ability to withstand, recover from, and adapt to external disturbances such as natural hazards, conflict, labour strikes or terrorist attacks (Mattsson and Jenelius,

2015). While there are many resilience frameworks, the most widely used one is the “4Rs” definition proposed by Bruneau et al. (2003) and later advanced by Tierney and Bruneau (2007). Here, the resilience of a technical system is determined by four interrelated dimensions: robustness, redundancy, resourcefulness, and rapidity. While the robustness and redundancy of the transport systems are seen as more static features of the network, the resourcefulness and rapidity are dynamics features that shape the resilience of the network (Mattsson and Jenelius, 2015). We discuss these concepts separately.

Robustness refers to the absorptive capacity of the system, i.e. the ability of a system to maintain functionality in case of failures of network nodes (e.g., station or ports) or edges (e.g., roads). The system robustness determines the extent and strength of cascading impacts of failures on the entire transport system. The concept of robustness is often approached from a network vulnerability, or criticality, perspective (Jafino et al., 2020; Wang et al., 2009). This describes the criticality of specific edges or nodes within the entire network. Methods to assess the vulnerability of network elements use graph characteristics, such as the betweenness centrality, or percolation methods (Jafino et al., 2020). Over the years, a large number of studies have emerged to identify the most vulnerable components of transport networks, such as for maritime (Calatayud et al., 2017; Peng et al., 2018; Viljoen and Joubert, 2016), road transport or rail transport networks (Dong et al., 2020; Pagani et al., 2019; Wang et al., 2019). However, recent literature has questioned whether graph-based metrics are indeed good proxies of the robustness of transport systems when compared to real-life networks and failure mechanics (Koks et al., 2023).

The redundancy of the system is commonly viewed as being related to the substitutability of edge connections within the entire system and is linked to the robustness. Within transport systems, this often reflect whether passenger or freight flows that under normal conditions move over the disrupted transport nodes or edges can be rerouted via alternative routes. Most previous studies use the network characteristics of the transport network as a proxy of the level of transport redundancy, for instance the OD k-connectivity, change in (weighted) accessibility, or the minimum link cut centrality (Jafino et al., 2020). Others have used dynamic transport models to test the redundancy of the transport system. Koks et al. (2023), for example, used a simplified passenger flow model for each country globally and evaluated the ability of the road networks to reroute local or regional disruptions. The authors found that most road transport systems have sufficient redundancies against localised failures, both less so for regional ones. Recently, Xu et al. (2024) analysed the path redundancies of the global liner shipping network and its ability to cope with localised disruptions due to tropical cyclones. They found that the liner shipping network is able to deal with mild cyclone events but may struggle to cope with extreme cyclone events given a lack of path redundancies, in particular for small island nations.

The resourcefulness of the transport system captures the ability to mobilise resources, such as materials, workers and other relevant resources (e.g., human capital), to cope with disruptions and recover quickly. Within the transport resilience literature, resourcefulness often captures the emergency resource deployment after disruptions in order to restore transport services (Yang et al., 2024). For instance, liner rescheduling strategies during disruptions, such as speeding up, port skipping, or port swapping could be interpreted as part of the resourcefulness of maritime liner networks (Li et al., 2015). In another study on multi-modal urban transport networks, the resourcefulness included the fixed amounts of emergency vehicles, supplies and personnel available to restore disrupted transport assets (Yang et al., 2024).

The fourth resilience dimension, the system’s rapidity, reflects a system’s ability to recover quickly after an external disturbance. This could reflect the speed of restoring specific assets, recovery of the network as a whole, for instance the freight volume or number of passengers handled. Most simulation models make ex-ante assumptions on the restoration duration of individual assets given a general lack of empirical evidence. However, the speed at which transport services can be restored is driven by many factors including the severity of the disruption, the resourcefulness, and organisational capacity, among other factors. A small number of studies have analysed empirical evidence on the restoration of transport systems after past disruptions. For instance, one study looked at 141 incidences of port disruptions, finding that median recovery duration is six days with a 95th percentile of 22 days (Verschuur et al., 2020). Others have looked at the recovery of public transport systems in China during the COVID-19 pandemic, finding that the recovery duration scaled with the size (i.e., number of passengers handled) of the public transport system (Wang et al., 2022).

Our review of the transport resilience literature here sketches the main developments of relevance for our topic but is non-exhaustive. We refer to other useful articles and more details to reviews of (Mattsson and Jenelius, 2015; Pan et al., 2021; Zhou et al., 2019). The relevant gaps in this body of literature are discussed further below.

2.2. Port choice modelling

Port hinterlands are often defined as the inland economic area influenced by ports and generate cargo flows from and to ports (Parola et al., 2021). Ports often compete in a large set of geographical markets, each with unique features resulting from differences in origin and destination flows, the configuration of transport networks, and demand for different cargo types (e.g., container versus dry or liquid bulk). There is a well-advanced literature on factors shaping port choice decisions of specific port hinterlands. For instance, port choice is determined, amongst other factors, by maritime access, port capacity, cost and efficiency, hinterland transport costs and times, as well as reliability and quality of transport services (Magala and Sammons, 2015; Mueller et al., 2020; Parola et al., 2021; Song et al., 2016; Zondag et al., 2010). Most port choice modelling approaches consider ports as being embedded within logistic chains, comprised of networks of origin or destination locations, maritime connections, port nodes, and hinterland connections (Song et al., 2016). All possible route combinations form the choice set, in which the probability of taking an alternative route (and hence port) is shaped by the generalised cost function which characterises the utility of that route. For instance, Zondag et al. (2010) construct a port choice model for four ports in the Le Havre-Hamburg range and NUTS 2 administrative regions across 12 European countries, finding that the port choice is particularly sensitive to port efficiency and the efficiency of hinterland connections. In a more recent study on European port competition, a port choice model for 31 European ports and 231 hinterland regions was constructed based on 11 port

choice factors that influence container imports from Asia to Europe (Mueller et al., 2020). Here, the authors found that hinterland transport costs, the number of port calls and the availability of a rail connection are the most important factors that determine the port choice.

Most of the port choice literature is concentrated in the Global North context, in particular in Europe and USA, given the availability of detailed data. Less is known about the factors that shape the port choice in the Global South context, such as in Africa. A survey of port choice determinants among shippers in Nigeria showed that ship call frequency, crane efficiency, terminal utilisation, and the distance between ports and warehouses are the most important factors that influence the port choice (Onwuegbuchunam, 2013). Haralambides et al. (2011) evaluated the port choice decisions in East Africa with a focus on eight countries (two coastal ones and six landlocked) and five ports (Mombasa, Dar es Salaam, Nacala, Beira and Durban). The authors considered the inland transport cost, inland transit time, ocean transport cost, and quality of port services as key choice factors, finding that the quality of services is most important in terms of the port choice. The same port choice modelling framework was also utilised to identify a suitable location for the construction of a new port in the East Africa port range.

2.3. Research gap

While there has been a large body of literature focusing on transport resilience, several knowledge gaps persist, which are the starting point of our research.

First, as was already mentioned in previous work (Verschuur et al., 2022b), there is a lack of studies looking at the resilience of transport networks that span the port-hinterland spatial scale. As mentioned in Section 2.2, most research either focus on maritime transport networks or city, regional or national road and rail transport networks. Recently, one study assessed the resilience of freight flows within the regional transport network, covering the port of Mobile and intermodal transport network (covering Mobile and Baldwin county), against extreme coastal flood events. This study found that the resilience of regional freight flows is dominated by the port's functionality (Tafur and Padgett, 2024). Another study focused on the resilience of the port-hinterland container transport network of the port of Gothenburg and seven regional dry ports in Sweden (Chen et al., 2017). The authors analysed three types of disruption scenarios which impact the seaport, dry ports and connecting routes. However, the spatial scale of these analyses is still relatively small and does not consider port substitution. Given the large spatial scale involved in port-hinterland networks, in particular for continents with large competing hinterlands (e.g., Europe, Africa and Asia), a resilience assessment necessitates taking a continental spatial scale.

Second, most transport resilience studies do not follow methodologies and theories used in mode or route choice modelling. For instance, while most port choice models utilise discrete choice methods to evaluate the shippers' choice preferences and utility (Ben-Akiva and Bierlaire, 1999; Zondag et al., 2010), discrete choice modelling is limitedly used in transport resilience assessments. Instead, most transport resilience studies that incorporate some form of transport flow modelling within their modelling framework use simple time or distance metrics as edge weight, and often use all-or-nothing type of flow allocation methods (Jafino et al., 2020). However, time or distance alone may not adequately reflect the choice behaviour of shippers, while all-of-nothing methods may be particularly crude for assessing transport redundancies. As such, there is still scope to analyse transport resilience in a way that is more consistent with the mode or route choice literature. Out of the four resilience dimensions mentioned, the redundancy metric is most relevant here, given the direct link between the two, as the initial port choice directly influences the possible alternatives. Moreover, there may be an efficiency versus redundancy trade-off. While port choice models try to maximise utility among a set of candidate ports, thereby favouring larger ports in close vicinity, redundancy refers to the ability to use alternative ports, routes or modes in case of disruptions. However, limited research has explored the integration of these two concepts. Building on an aggregate logit route choice model calibrated on observed flows (Tavasszy et al., 2011), Halim et al. proposed a scenario discovery approach to the global container transport network. Specifically, they assessed the robustness of the Rotterdam port-hinterland system (Halim et al., 2016) against a range of uncertain futures (e.g., a deteriorating quality of the port and hinterland connections). Still, the redundancy of the port-hinterland system against specific shocks or disruptions is not assessed, leaving substantial scope to explore this.

Third, while most studies look at the resilience of the current transport networks, there has been limited attention for changes in the resilience of the transport system as a result of new transport projects. In geographical settings with expected surges in transport investments, such as in Africa and Asia, this is an important shortcoming. In fact, resilience dimensions could be included in the planning process of new transport projects, whether port expansion, modernisation or greenfield projects. There are currently limited insights whether synergies or trade-offs exist with respect to transport resilience and conventional transport planning objectives such as improving accessibility.

3. Methodology

3.1. Overview

Our methodology consists of a number of components. First, we discuss the different data sources we use for the analysis (Section 3.2), including the representation of hinterland regions, ports, and the various cost and time components to connect the two. This is followed by the port choice modelling between hinterland regions and ports (Section 3.3) and the formulation of the utility function adopted (Section 3.4). Afterwards, we discuss the conceptualisation of the port-hinterland redundancy (PHR) metric (Section 3.5). Section 3.6 covers the two disruption scenarios tested, whereas Section 3.7 describes the two investment scenarios tested.

3.2. Data sources and hinterland processing

We consider a variety of data sources and preprocessing for our analysis: (i) a selection and delineation of the hinterland regions, (ii) port container throughput, and (iii) routes choices between hinterland and ports with associated travel times and transport costs.

To characterise the African hinterland regions, we consider 779 administrative regions (administrative 1 level as specified in the Global Administrative Areas Database, GADM) across the African mainland and Madagascar, covering 50 countries. We exclude other islands as their choice set is too limited to include in the analysis.

The number of ports to be included is 100, covering all major container ports across the continent. For each port, we collect information on the container throughput (in TEU). The TEU throughput per port is derived based on a stepwise gap-filling approach. First, we collected data on official container throughput for 28 ports. As a first gap-filling strategy, we try to approximate container throughput based on container moves data (i.e., the number of container moves irrespective if TEU or FEU), which we obtained from S&P Global as part of the data included in the World Bank Container Port Performance Index ([The World Bank, 2024](#)). We have overlapping data for 19 ports. We set up the following regression:

$$TEU_p = \alpha_0 + \beta_1 M_p \quad (1)$$

with p the port. We find a R^2 of 0.81 with $\alpha_0 = 8,389$ and $\beta_1 = 1.298$ ($p < 0.01$). We use this regression to fill data gaps for the ports we do not have official TEU data, but do have container moves data (29 ports).

For the remaining 53 ports, we approximate the TEU throughput based on annual container port call data based on Automatic Identification System (AIS) data, as done in previous work ([Verschuur et al., 2021](#)). We set up a regression between TEU and DWT, for which we have a sample of 28 ports. We adopt the following formulation:

$$TEU_p = \alpha_0 + \beta_1 DWT_p \quad (2)$$

We find a R^2 of 0.54 with $\alpha_0 = -1.77e^4$, $\beta_1 = 0.047$ ($p < 0.01$). We use this regression to fill data gaps for the ports we do not have official TEU nor container moves data (53 ports). The validation plots of the two regression models are shown in [Supplementary Fig. 1](#) and the estimated throughput per port in [Supplementary Fig. 2](#).

To connect each administrative hinterland region to the respective ports, we construct a continental-scale transport network based on OpenStreetMap, which nowadays has an almost complete coverage of global road and rail networks ([Barrington-Leigh and Millard-Ball, 2017](#)). As a baseline, we only consider the road transport network, whereas for the investment strategy scenario (see [Section 3.7](#)) we will also add the existing railway network. We add several time and cost components to the hinterland transport network, including travel speed, border dwell time, transport distance costs (in USD per t-km), port dwell and container handling cost. This data has been derived in previous work ([Verschuur et al., 2025](#)) by integrating a variety of public sources, which are summarized in [Supplementary Table 1](#). We derive the shortest path between all administrative regions and the ports they are connected to minimising the generalised cost (GC) formulation used in previous work ([Verschuur et al., 2025](#)), which can be written as a function of country (c) and mode (m):

$$GC_{c,m} = dc_{c,m}D_m + VFTT_{c,m}(T_m + W_{c,m}) + Hc_{c,m} \quad (3)$$

With dc the distance costs (USD per t-km), D the travel distance (km), T the travel time, W the waiting or dwell time (at ports, borders, origin, destination or rail terminal), and Hc the handling and border compliance costs (port handling or (un)loading at origin, destination, or rail terminal). The value of freight travel time (VFTT) can be interpreted as the marginal rate of substitution between travel time and costs ([Binsuwadan et al., 2022](#)). The generalised cost function used includes both distance-based cost and time-based cost, reflecting the fact that distance and time are not always perfect substitutes within the African context, mainly due to large speed differences between main highways and secondary roads, and the long waiting times at border crossings (ranging from a few hours to multiple days) ([Arvis et al., 2010](#)).

For each shortest path, we can extract the corresponding transport cost and time for each feasible hinterland-port pair. For road connectivity, this includes 74,238 feasible pairs, whereas for rail connectivity this includes 3,166 feasible pairs. This difference can be explained by the fact that almost all ports can be connected to hinterland regions via the road network, even if a majority will not be used in reality. For rail, only a subset of all container ports have a rail terminal close by (64 ports), and these rail terminals only connect to a subset of hinterlands (532 administrative regions can reach at least one port via rail).

3.3. Port choice model

We start by estimating the port choice, which captures the market share of each port at a particular hinterland. The most common way to capture the port choice is a via an utility-based approach ([Zondag et al., 2010](#)). Utility captures the combination of factors that users value when deciding what routes to take or places to visit, in our case which port to use when sending or receiving goods. For port-hinterland choices, this includes factors such as maritime access, port capacity, hinterland transport costs and times, and the reliability of hinterland transport services. The port choice set per hinterland region, the set of ports used for trading, reflect this utility.

We first estimate the port choice probability. Within ex-ante analysis (that is, when the relative port choice is not known), this includes quantifying the probability (P) that shippers in a region choose a certain port. The choice P is defined following the logit formulation, often adopted in port choice modelling ([Magala and Sammons, 2015](#); [Mueller et al., 2020](#); [Zondag et al., 2010](#)):

$$P_{jn} = \frac{\exp(V_{jn})}{\sum_j \exp(V_{jn})} \quad (4)$$

With n the different hinterland regions (one of the 779 administrative regions as defined in Section 3.2), j the alternative ports, and V_{jn} the utility that shippers in region n obtain from sending or receiving goods through port j . J is the port choice set for each hinterland. In our analysis, we connect each hinterland location to each port that this hinterland can reach via the transport network ($J = 100$).

Using P_{jn} , we can for each port derive the market share across the wider hinterland. For each hinterland, we can derive the likely share of container flows going through a certain port. We can use this to construct a port concentration (PC) metric for each hinterland, which gives us an indication how a hinterland's container trade is concentrated across the port choice set. We use the PC as the smallest number k such that the top k ports account for at least 95% of total choice probability. To do so, we first rank the port choice for each hinterland region:

$$P_{n1} \geq P_{n2} \geq P_{n3} \dots \geq P_{nJ} \quad (5)$$

$$PC_n = \min \left\{ k \in \{1, \dots, J\} \mid \sum_{j=1}^k P_{nj} \geq 0.95 \right\} \quad (6)$$

A smaller PC implies higher concentration (few dominant ports), whereas a larger PC implies a more distributed port choice.

3.4. Characterisation of utility function

The utility function should be derived empirically based on survey data on port choices. However, doing so is not straightforward, in particular within the African port context where such data is not readily available. As such, we take a simplistic, yet necessary, approach and use the utility function derived in previous work of Haralambides et al. (2011). In this study, the authors studied the port choice for six hinterland regions (countries in this case) and five container ports in the East African port range (Dar es Salaam, Mombasa, Nacala, Beira and Durban). Based on revealed port choices, the authors could derive the following utility function which describes the utility for a certain route between j and n as:

$$V_{jn} = \alpha_0 TC_{jn} + \alpha_1 \ln(TEU_j) + C \quad (7)$$

with TC the total cost, capturing both port and hinterland distance costs (USD/t), TEU the total port throughput in TEU, and C a constant irrespective of the route chosen. In other words, a shipper assigns a higher utility to routes with lower distance costs that connect to larger ports (i.e., as they likely have better maritime connectivity).

The coefficients (α) represents how shippers value these two factors, which together shape the observed choices. The coefficients are based on the choice modelling results of Haralambides et al. (2011), who found values of -0.031 for α_0 , 0.853 for α_1 and 0.068 for C . Within a data scarce context, like in Africa, it is hard to validate whether extrapolating this utility function to the whole continent can be justified. We acknowledge that this is a major limitation. However, in another study with a focus on the West-Africa region (Veldman, 2019), a coefficient of -0.03 was found for the inland transport costs in their utility function. This reinforces the idea that this coefficient can be applied uniformly across the continent. To test how sensitive our results are the chosen parameters (α_0 and α_1), we perform a sensitivity analysis in which we change the parameters with 20% up or down. We will report these alternative results in the Supplementary Materials. Still, future research can test our methodology with a more refined utility function that uses factors beyond the two considered here, such as port efficiency, feeder/hub functionality, cargo type, hinterland reliability and time effects.

3.5. Definition of port-hinterland redundancy

Transport redundancy is commonly defined as the "extent to which elements, systems, or other units of analysis exist that are substitutable, i.e., capable of satisfying functional requirements in the event of a disruption, degradation, or loss of function" (Bruneau et al., 2003). Within the transport resilience literature, network redundancy often conceptualised in terms of travel alternatives (both mode and routes) or in terms of residual or spare capacity in the network (Xu et al., 2018). Others have linked redundancy (sometimes called 'substitutability') to the ability of substitute preferred travel alternative(s) with less preferred ones (van Wee et al., 2019). The preference for certain alternatives is then captured by its utility, which can include factors such as time, distance, capacity, among others.

There is, however, no generally accepted definition of PHR (Verschuur et al., 2022b). In this paper, we build upon the aforementioned literature and define PHR as the extent to which the preferred port alternative(s) can be substituted by other initially less preferred port alternatives. We analyse the PHR thus from the perspective of a specific hinterland region (one of the 779 administrative regions considered). The preference for a certain port is expressed by the port choice, which in turn is a function of the utility derived from using a certain port. As such, the PHR is measured by the loss in utility across the set of ports used (the choice set J) in case a port or route connecting port to hinterland is facing a disruption. A high PHR implies that a hinterland will face relatively limited utility loss if a disruption of the preferred port alternatives occur, whereas a low PHR implies the opposite. From a port-hinterland systems point of view, the PHR is therefore shaped by the location of ports along the coastline, their capacity, but also the transport frictions to connect hinterland location to coastal ports.

Deriving the PHR therefore requires first estimating the total utility derived across the choice set. This is equivalent to the measure of port-hinterland accessibility, which is defined as the ease of reaching or deriving value from coastal ports. Here, we use the LogSum (LS) as a measure of the accessibility of hinterland regions with respect to coastal ports, the most widely used measure of accessibility (Geurs and van Wee, 2004). The LS metric can be written as:

$$LS_n = \ln \left(\sum_j e^{V_{jn}} \right) \tag{8}$$

The LS metric can be interpreted as the expected maximum utility a shipper derives from making a choice among J ports in the choice set (Ben-Akiva et al., 2008; Ben-Akiva and Bierlaire, 1999). The LS metric is continuous and can change due to changes in the number of alternatives (e.g., a new port) and factors that affect the utility (e.g., reduced travel time or costs), making it an important metric to evaluate the system-wide benefits of transport policies.

In case one or multiple ports out of the port set are disrupted, alternative, lower utility, ports and routes have to be used for trading (if available and/or feasible), which results in a reduction of the hinterland’s accessibility value. We formulate the redundancy (R) as the inverse of the loss in accessibility, following one or multiple port disruptions. In other words, the higher this loss, the lower the redundancy. We quantify the change in the LS when we remove the disrupted ports (D) from the port choice set J (LS^D), with D being a set of disrupted ports (d):

$$R_n = \frac{1}{LS_n - LS_n^D} \tag{9}$$

The level of accessibility without the disrupted ports D is shaped by the probability P_d that a disrupted port d is chosen, as higher probability ports contribute more to the overall accessibility. Finally, we normalize the R_n between 0 and 1 for ease of interpretation:

$$\hat{R}_n = 1 - \frac{1}{1 + R_n} \tag{10}$$

A \hat{R}_n of (near) one implies that the omission of disrupted ports lead to limited changes in the accessibility whereas a \hat{R}_n of (near) zero implies the region derived its total utility almost exclusively from the disrupted ports. It is important to note that this formulation only works when two or more options are available, hence why we exclude small islands (see Section 3.2).

3.6. Disruption scenarios

We analyse the redundancy level against two types of disruptions: (i) a random single-port disruption and (ii) a regional disruption covering one or multiple ports. For the single-port disruption, we assess the redundancy against a disruption of the highest choice probability port only. The single-port disruption scenario resembles a port failure due to an external disturbance that is geographically uncorrelated, i.e., an energy outage or localised extreme weather event (landslide or local flood event). The disrupted port set thus covers:

$$D_n \in \{P_{n1}\} \tag{11}$$

For a regional disruption, we assess the redundancy against a disruption of the highest choice probability port and geographically close ports. The regional disruption scenario resembles an external disturbance that is geographically clustered, i.e., a national labour strike, regional conflict or widespread extreme weather event (e.g., earthquake). We include this distinction as the redundancy of a system is event-specific and can differ depending on the severity and spatial extent of the disruption. We model this regional disruption for all ports within a geographical distance of the highest choice probability port:

$$D_n \in \{P_{n1}, \dots, P_{nj}\} \tag{12}$$

With P_{nj} included if:

$$d(P_{n1}, P_{nj}) \leq R \tag{13}$$

With d the geographical distance between the highest probability ports and the other ports in the choice set, and R the radius around the highest probability port. Hence, the regional disruption scenario includes the single-port disruption scenario and extends this to a multi-port disruption situation in case other ports are in a close vicinity to the highest choice probability port. We could test the regional disruption scenario with different values of R . Here, we choose $R = 200$ km and $R = 1000$ km to evaluate the how different spatial footprints impact the PHR metric. A 200 km spatial footprint could be interpreted as a moderate cyclone or earthquake, regional power outages, or regional conflict. A 1000 km spatial footprint could be interpreted as being equivalent to an extreme cyclone or earthquake, national labour strike, or large-scale conflict event. We consider the single-port scenario as the base scenario and compare the PHR of the regional disruption scenario with respect to the base case.

3.7. Investment scenarios

The accessibility of port-hinterlands can be improved in different ways, for instance via investments in transport infrastructure (e.g., corridor developments), reducing dwell time (at ports or borders), investments in alternative modes of transport (rail, inland water), or by expanding ports (thereby improving maritime services). We evaluate the impacts of two investment types on the respective accessibility and PHR of port hinterlands: port expansions and rail modernization investments.

First, we evaluate the impacts of six major port investments that are planned; the construction of the Ndayane port (Senegal, first phase will increase container handling capacity by 1.2 million TEUs), the Lamu port expansion (Kenya, 1.2 million TEU), the expansion of the port of Maputo (Mozambique, 0.65 million TEU), the expansion of Berbera port (Somalia, 1.5 million TEU), the port of Durban’s envisioned expansion (South Africa, 7 million TEU), and the container expansion of Tema (Ghana, 1.2 million TEU). For the Ndayane port, we add the port and its TEU throughput to the port choice set ($N = 101$). For the other port expansions, we add the throughput to the existing throughput values. This changes the utility between each hinterland-port pair and hence the port choice, accessibility and redundancy metric.

Second, we evaluate the accessibility and redundancy trade-off when we considering railway networks as a mode of transport to

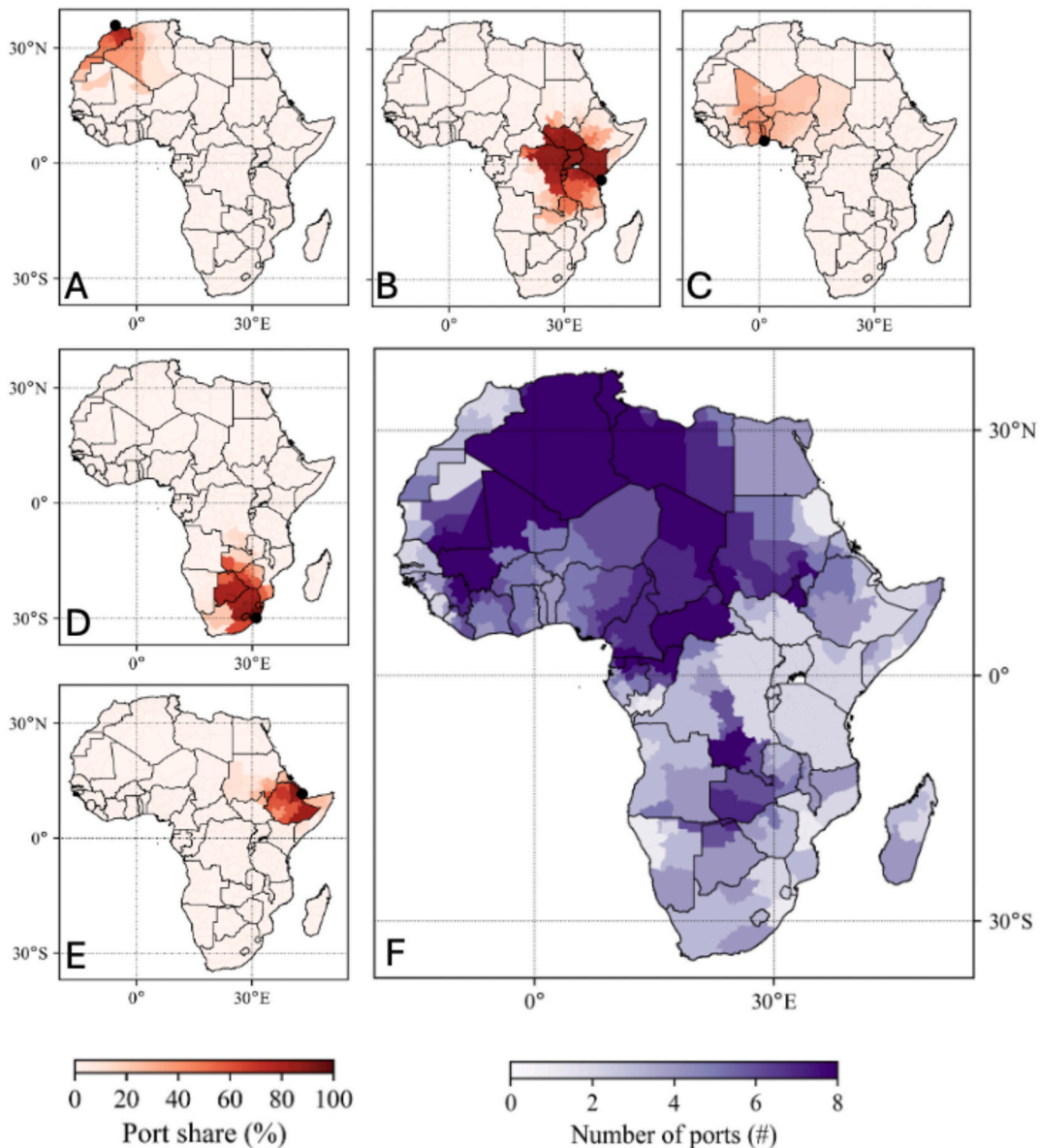


Fig. 1. (A-E) Port choice probability across the continent for five major ports, including Tangier-Med (A), Mombasa (B), Lóme (C), Durban (D) and Djibouti (E). (F) The number of ports that contribute to at least 95% of the choice probability set of the hinterland.

link hinterlands to ports. Here, we assume for simplicity that the railway connection has sufficient capacity to handle containers. To do so, for the set of hinterland-port pairs for which rail connectivity exist, we evaluate the rail transport cost alongside the road transport cost. We replace the transport cost in the utility function (Eq. (7)) if the rail transport costs are lower than the road transport cost. In essence, this increases the ability of certain hinterlands to reach ports at a greater distance, which changes the port choice probabilities, and hence the accessibility and redundancy metrics.

In both investment scenarios, we evaluate the impact (Δ) of the investment strategy (i) separately. Specifically, the impact of the

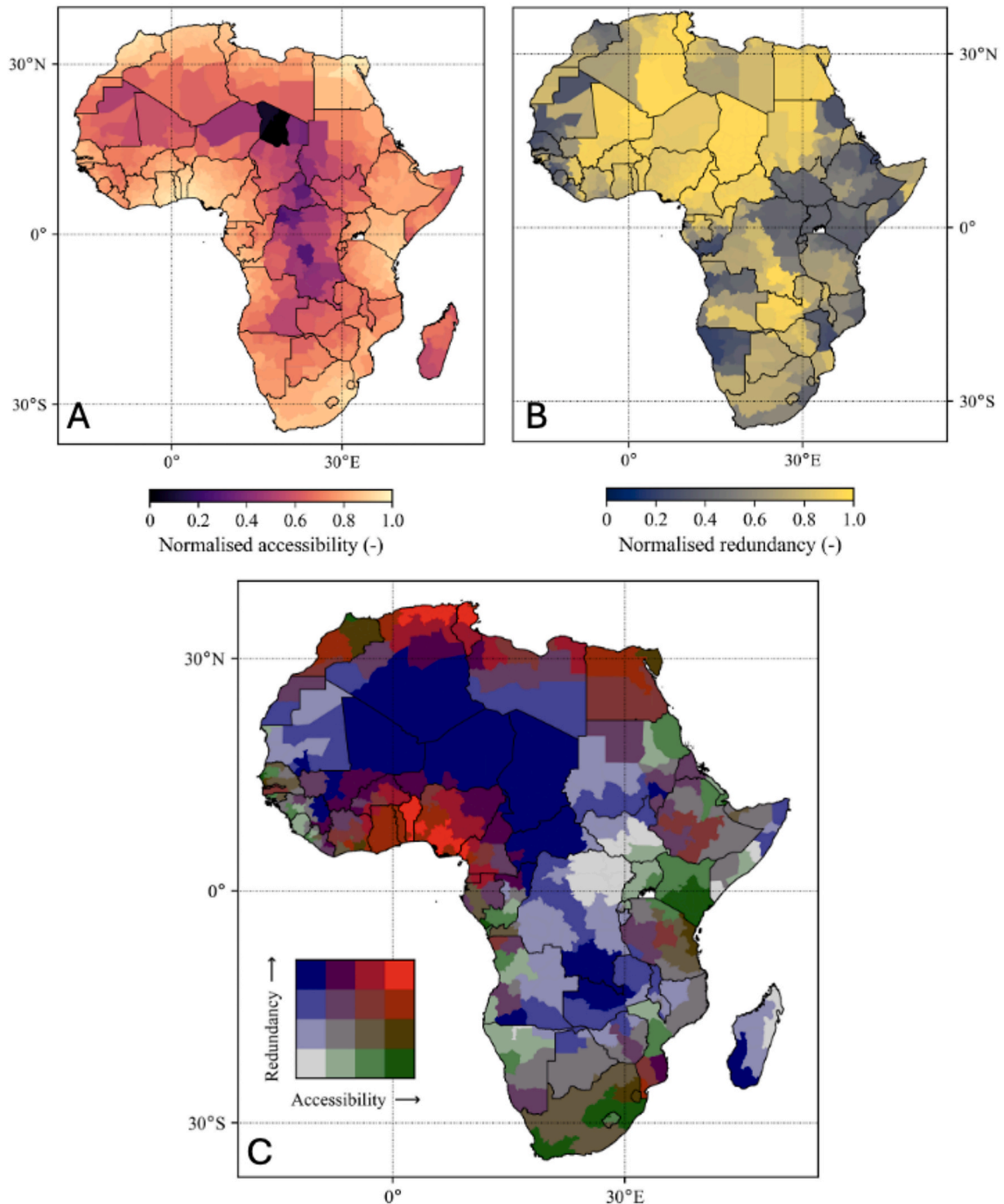


Fig. 2. (A) Port accessibility indicated, normalised between 0 and 1 across hinterland regions. (B) The normalised redundancy indicator for the single-port disruption. (C) Classification of hinterlands regions based on the accessibility and redundancy indicator. This classification is derived by mapping each region in quantiles based on their redundancy and accessibility scores.

investments on accessibility can be measured as:

$$\Delta LS_{i,n} = LS_{i,n} - LS_n \quad (14)$$

with is by definition positive, as we only consider investments that improve utility. The impact of the investments on PHR can be measured as:

$$\Delta R_{i,n} = \hat{R}_{i,n} - \hat{R}_n \quad (15)$$

which could be either positive or negative, as it can reinforce the existing dependency on preferred ports or increase the dependency on non-preferred ports.

4. Results

4.1. Port choice

We start with our results of the port choice probabilities (Eq. (4), which form the basis for the PHR analysis. Fig. 1A–E shows the port choice for five major container ports across the different port ranges – Tangier Med (Fig. 1A), Mombasa (Fig. 1B), Lomé (Fig. 1C), Durban (Fig. 1D) and Djibouti (Fig. 1E) – showing the regional hinterland they serve. Durban is the key port serving South Africa and landlocked countries in Southern Africa (Lesotho, Botswana, Zimbabwe), while Tangier-Med serves large parts of Morocco and Algeria. Mombasa is an essential port for landlocked countries in Central Africa, while Djibouti is the main gateway for Djibouti, Ethiopia and parts of Sudan. In West Africa, stark port competition among container ports shapes the port choice, with regional hinterlands being served by multiple ports. Hence, the port of Lomé has a low choice probability across a vast hinterland area in Western Africa.

Fig. 1F illustrates the number of ports that cover at least 95% of a region's port choice, our indicator of the port concentration (Supplementary Fig. 3 shows the results for the sensitivity analysis). Not surprisingly given the geography of Africa and the location of major container ports, most regions have only a small number of ports serving the region. 33% and 69% of regions depend on less than two and five ports, respectively, to serve their hinterland. On the other hand, parts of the Sahara region, as well as regions in Algeria and Tunisia, depend on a more varied set of container ports, given that multiple (smaller) ports can serve these areas.

4.2. Accessibility and redundancy against localised disruptions

Given the disparities between countries in terms of transport time, distance, port availability and capacity, both our accessibility and redundancy metrics can strongly from one place to the other. Our work allows for a continental-scale comparison of the geographical differences of the regions' accessibility and redundancy, and their underlying drivers.

The accessibility measure as defined in this work shows that coastal regions in the vicinity of major container ports have a high accessibility, whereas regions located in landlocked countries have a low accessibility (Fig. 2A, see Supplementary Fig. 4 for the results of the sensitivity analysis). On the other hand, some of these low accessibility regions have high redundancy for localised disruptions (see Fig. 2B, see Supplementary Fig. 5 for the results of the sensitivity analysis). For instance, despite low accessibility of regions in the Sahara region, they have an almost equal utility to access ports in the West-African port range, the Northern Africa port range, and the North-Eastern part of Africa. A similar observation is made for regions in Zambia and the south of DRC, which have low accessibility in general, but can choose between containers ports on both side of the continent. Regions with low redundancy are located predominantly in coastal areas close to a major seaport, but without an alternative seaport close by, such as in Namibia, Senegal, Congo, Kenya and parts of Mozambique and Ethiopia (see Fig. 2B).

We can now classify regions according to their accessibility and redundancy metrics (based on four quantiles), as shown in Fig. 2C. We can find three clusters of both high accessibility and redundancy, which are in Egypt, Tunisia plus Northern Algeria, and in the Western Africa port range (Ghana, Togo, Benin, Nigeria, Cameroon). Regions with high accessibility and low redundancy are the aforementioned coastal cities relying on a single major port. Regions with low accessibility and high redundancy are some of the landlocked regions (Zambia, Zimbabwe, Niger, Chad) that are served by multiple ports across different port ranges. One can also identify places with low accessibility and low redundancy, pockets of which are located in Mauritania, South Sudan and the DRC. It is important to note that our redundancy metric should always be interpreted with the accessibility metric in mind. For instance, places with high redundancy, but low accessibility may be able to switch ports, as they depend on a multitude of ports for trade, but still face substantial transport frictions in doing so.

4.3. Redundancy against regional disruptions

High redundancy in many of the regions is driven by the fact that there are multiple, equally accessible ports that could serve this particular hinterland. However, while these port-hinterland systems could provide redundancy against targeted disruptions, they may still be prone to regional disruptions, i.e., disruptions that affect multiple ports within a wider geographical area.

Fig. 3A show the change in the redundancy metric when adopting the regional disruption scenario (200 km distance) compared to the single-port disruption scenario. We observe a reduction in redundancy in Egypt and parts of Western Africa (Togo, Benin, Burkina Faso). This pattern is reinforced when looking at the 1000 km buffer area (Fig. 3B). In this scenario, most regions face some additional

loss in redundancy, with hotspots, alongside the earlier mentioned regions, also visible in Somalia, Mozambique and Eritrea.

4.4. Accessibility and redundancy trade-off of transport investments

The Ndayane port expansion, which is intended to replace the current Dakar port in the long run, will have a positive accessibility impact on the hinterlands that are now served by the Dakar ports (Supplementary Fig. 6A). Moreover, it improves the redundancy in Senegal and its neighbouring countries (Guinea and Mauritania) (Fig. 4A), with an overall redundancy benefit of 2.7% across the continent. In a similar vein, the expansion of the Lamu port will benefit the hinterland region that is currently served by the port of Mombasa (see Fig. 4B and Supplementary Fig. 6B). This is also the main objective of the project; to resolve the congestion issue at the port of Mombasa and its environmental impacts to the city. Moreover, the expansion will positively affect the redundancy of the hinterland, improving the continent-wide redundancy by 11.7%. Lamu becomes the main port of choice for hinterlands in Kenya, Tanzania, Uganda, South Sudan and parts of DRC. In other words, major new port developments can have strong redundancy benefits by providing hinterlands served primarily by one port with a suitable alternative.

The expansion of existing container ports can, however, induce a redundancy trade-off (Fig. 4C–F). On the one hand, the redundancy of the core hinterland (the hinterland that already has a high choice probability) can decrease given that the accessibility to the port is further reinforced, making alternatives less attractive. On the other hand, the redundancy of the hinterland periphery (i.e., hinterlands with a low or negligible choice probability) increases, as the terminal investments allow these hinterlands to divert flows towards the new port expansion. The net redundancy is positive for three of the four expansions, with net benefits of 1.8% (Maputo port), 0.8% (Berbera port) and 2.0% (Tema port), while net negative change is observed for the expansion of Durban (−1.4%).

In case of significant rail investments, which can lower the transport costs considerably for connected hinterlands, major accessibility improvements can be made (Fig. 5A). This is particularly true for regions in landlocked countries that have a good railway connection to one of the major ports, such as parts of Botswana (connected to the ports of Maputo and Durban), Zimbabwe (connected to the port of Beira), and parts of Algeria (connected to the port of Oran). Overall, accessibility improves by 1.9% across Africa. However, adding railway connections to the hinterland transport network can also cause an overreliance on rail routes, having implication for the PHR (Fig. 5B). While the net redundancy improves by 4.9%, it can reduce the PHR for the Sudan, Nigeria, Ivory coast, and Cameroon.

5. Discussion and policy implications

Improving the accessibility between ports and hinterlands has large economic benefits by lowering trade costs, thereby enabling a growth in trade. Yet, in hinterlands with limited port-hinterland redundancies, the overreliance on a single or small number of ports can cause negative economic impacts in case of port disruptions. In this paper, we have adopted the concept of transport redundancy

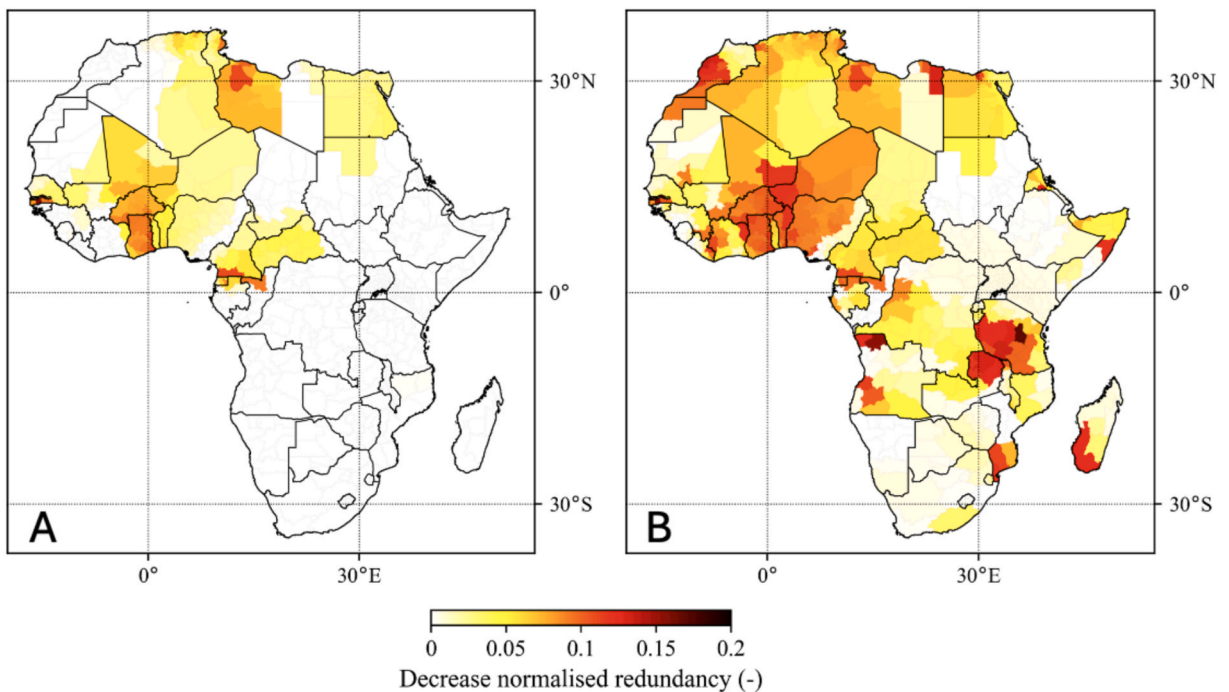


Fig. 3. (A) The reduction in normalised redundancy as a result of a regional disruption scenario, with a buffer of 200 km, compared to the single-port disruption scenario. (B) Same as (A) but for a 1000 km buffer.

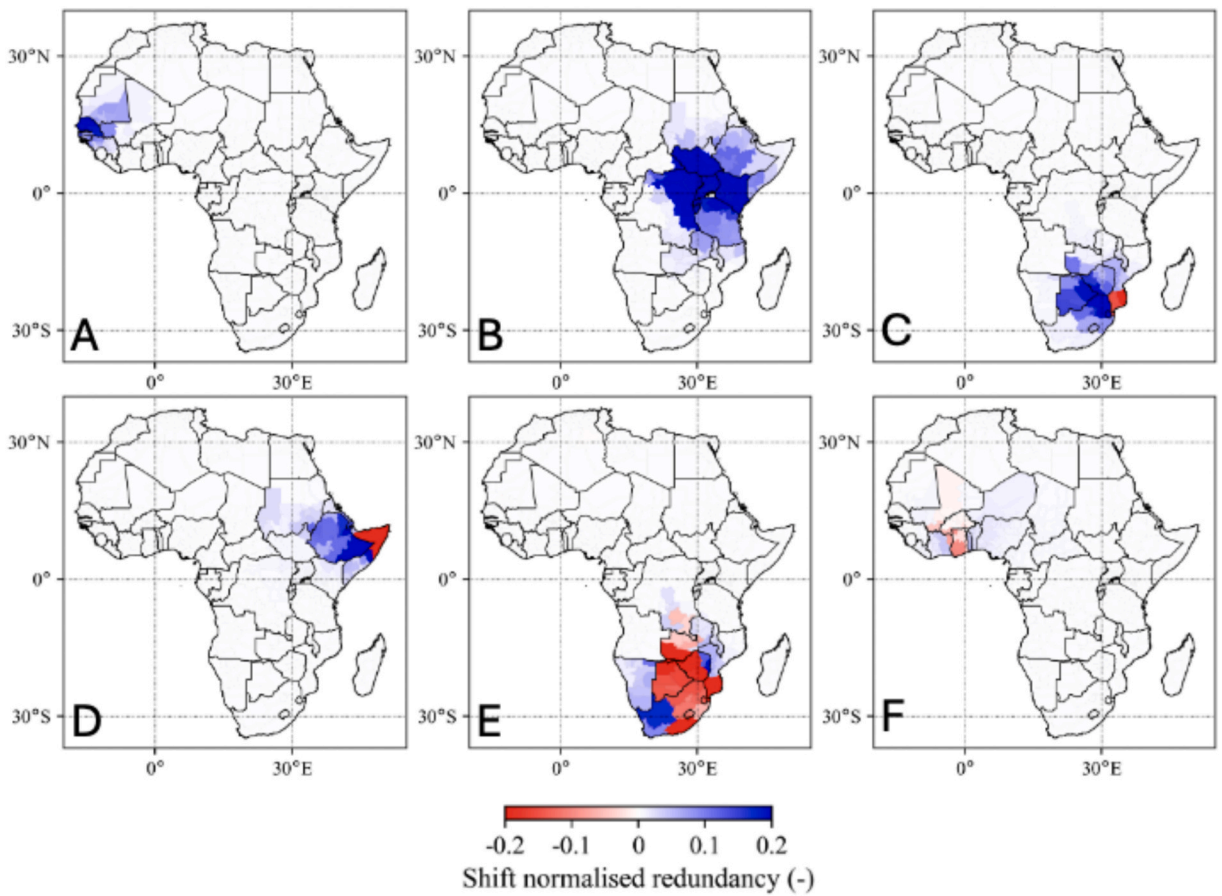


Fig. 4. (A-F) The change in normalised redundancy for six port investments under the single-port disruption scenario; Ndayane (A), Lamu (B), Maputo (C), Berbera (D), Durban (E), and Tema (F).

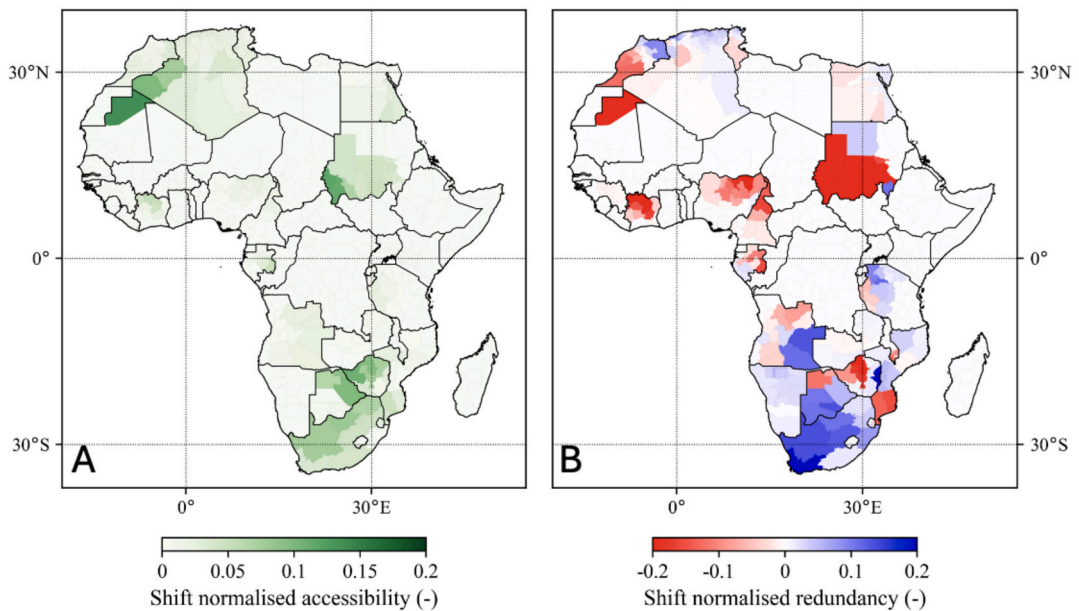


Fig. 5. (A) The change in accessibility after adding railway connections between hinterlands and ports to the model. (B) Same as (A) but for the redundancy metric under the single-port disruption scenario.

and applied it to the African port-hinterland transport system, a continent with a small number of major container ports and large transport frictions. Insights into the redundancy of port-hinterland systems can have wider implications for policy and planning in Africa, but also other geographies. We discuss these implications below.

We identified regions based on their degree of accessibility and redundancy. This is important to, ex-ante, predict the likely impacts of disruptions at ports. For instance, clusters of regions with high accessibility and low redundancy (Namibia, Senegal, Kenya) will likely face high rerouting costs in case of port disruptions, given that access to alternative ports is limited. Regions with low accessibility and low redundancy, such as Mauritania, South Sudan and the DRC will likely face supply shortages under disruptions, as rerouting may not be feasible or too expensive. On the other hand, regions with high redundancy (Zambia, Zimbabwe, Niger, Chad) have the potential to reroute goods via alternative ports at relatively limited additional costs, at the backdrop of substantial transport frictions to start with. The most resilient regions from a port-hinterland perspective are located in coastal region of Northern Africa and parts of Western Africa. These insights can be embedded within risk models of port disruptions (Verschuur et al., 2023) to better capture how the resulting economic losses of port disruptions may differ based on the port-hinterland configuration (Verschuur et al., 2022b).

Apart from testing the hinterland redundancy based on a single-port disruption (the preferred port), we also considered a disruption scenario that could capture a disruption to both the preferred port and ports within a geographical proximity of this port. Not surprisingly, this will mainly reduce the redundancy in hinterlands that depend on a set of ports that are close to each other, such as Egypt, Somalia, Togo and Benin. In other words, the redundancy can vary according to the type of disruption that is being considered. It should be noted that our redundancy metric cannot capture the complex impacts of regional disruptions, in particular large-scale simultaneous disruptions. In such cases, the redundancy is also determined by the available capacity in substitute ports and on routes, as well as the logistical feasibility to divert goods to other ports. Exploring these aspects is a promising future research avenue.

We show that investments that improve port-hinterland accessibility can have synergies and trade-offs with redundancy. Construction of new ports will almost by definition improve the redundancy (except when it replaces an existing one), and hence targeted greenfield port developments can help improve the redundancy of port-hinterland systems. Port expansions can have both positive and negative contributions to the redundancy of port-hinterland transport systems. By attracting more traffic within its existing core hinterland (with already high port choice), the redundancy can decrease, whereas in the hinterland periphery, the redundancy can increase. For the six port investment projects analysed, urban regions close to the expanding ports can diminish their redundancy, while landlocked African countries primarily benefit. Some of the hinterland regions of influence also overlap between the investments, and as such interactions between these investments should be considered in planning and future work.

Railway investments can similarly have positive and negative effects. On the one hand, given the cost competitiveness of railway, overreliance on rail connections to major ports can diminish the redundancy. On the other hand, for many regions, railway accessibility can widen the subset of ports it can access cost-efficiently, improving their redundancy. For instance, at present, there is an overreliance on routes connecting mines in Zambia and DRC to the ports of Durban and Dar es Salaam, corridors that both experience frequent delays and shutdowns (King, 2024). In response, the planned Lobito Corridor, connecting the same mines via rail to the Lobito port in Angola, will help improve the redundancy of the hinterland transport system. System-wide information on port-hinterland redundancies is key for the prioritization of regional investments and should feed into transport investment evaluation assessments. Apart from the applications and types of investments discussed in this paper, the concept of port-hinterland redundancy can help inform investments in port-hinterland transport corridors that are being planned at present across Africa, which can similarly reduce or increase the redundancy of hinterland regions.

We believe that the redundancy metric as adopted here is a useful ex-ante method for capturing one component of the port-hinterland transport resilience. However, further work is needed to evaluate how our redundancy metric compares to other approaches to quantify system-wide redundancies, for instance using freight models (Koks et al., 2023). Freight models are hard to set up on a large scale, given the computational complexity and need for calibration. However, they have the benefit that they can include port and hinterland capacity constraints, and can simulate the response of freight flows to disruptions. Moreover, our PHR metric could be complemented with other resilience indicators of port-hinterland resilience, such as the ability of ports and transport routes to cope with disruptions, factors that shape the recovery of freight flows after disruptions, and the level of preparedness (e.g., early warning and emergency response systems). Combine these indicators with our PHR metric would allow for a better classification of the resilience of port-hinterlands across the different resilience dimensions.

It should be noted that we do not advocate for our port-hinterland redundancy metric as the primary decision variable when making decisions. Investing in larger, more modern, ports can have substantial benefits, such as benefits from economies of scale and wider agglomeration effects (Fujita and Mori, 1996), even if it comes at the expense of reduced port-hinterland redundancy. Moreover, investing substantial resources in potentially underutilised ports may impede the financial viability of such investments in the short-run. In other words, the optimal strategy to hedge against the probability of large-scale disruptions at the expense of increased operational expenses may differ across context, for instance depending on the risk profile of the port-hinterland corridors, the magnitude of the efficiency-reliability trade-off, and the risk tolerance of the decision-maker. We do like to emphasise that port diversification should not be considered as the sole strategy to deal with limited port-hinterland redundancy. For instance, emergency management strategies (e.g., emergency inventories) and early warning systems (that monitor disruptions en route) can help anticipate disruptions, and cope with them. Moreover, innovative financial instruments are starting to emerge, such as the pooling of firm resources to improve the resilience of strategic transport routes (including ports) or parametric insurance for transport operators (Punte, 2025), that could be considered as complementary resilience strategies.

6. Conclusion

Our research has highlighted that new investments should balance accessibility and resilience. The price that shippers are willing to pay for resilience depends on the expected risks, including their likelihood and impact. These factors should be carefully considered for each hinterland region, with our modelling framework providing a useful starting point to do so. Despite this, within the context of the African continent, where large investments decisions will need to take place in the next few decades, there is a window of opportunity to mainstream resilience considerations in investment planning. In conclusion, analysing port-hinterland redundancies thus has the potential to improve freight transport planning decisions as well as disaster risk analyses, in particular quantifying systemic risks of freight transport systems.

CRedit authorship contribution statement

Jasper Verschuur: Writing – review & editing, Writing – original draft, Formal analysis, Conceptualization. **Lori Tavasszy:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.tra.2026.104920>.

Data availability

The data and code to reproduce the results will be uploaded to the following Zenodo repository (<https://zenodo.org/records/18518567>).

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