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The Increasing Importance of Ro-Ro (Roll-On/Roll-Off) Transportation in the Mediterranean

U. Demir
Piri Reis University, Istanbul, Turkey

ABSTRACT: A key component of multimodal logistics in the Mediterranean, roll-on/roll-off (Ro-Ro) shipping is beset by increasing capacity limitations, environmental regulations, and port coordination gaps. This study creates an integrated framework for improving current and future Ro-Ro routes by bridging two previously discrete approaches: AIS-based Geographic Information System (GIS) traffic analysis and expert-driven Analytic Hierarchy Process (AHP) weighting. Consistent priority weights were obtained from paired comparisons provided by twenty domain experts (CR = 0.032). These weights were superimposed on basin-wide AIS density layers in September 2024 to identify underserved routes and bottlenecks. The results show that while green corridor potential in the Eastern Mediterranean is still mostly unrealised, high-frequency handling capacity, intermodal connectivity, and advanced port community systems collectively account for more than 27% of the variance in route performance. Three of the five candidate routes that the framework creates from a selected shortlist offer travel time reductions of more than 18% when compared to existing services. The work contributes to the field of maritime logistics by showing how evidence-based corridor planning can be supported by spatially contextualising multi-criteria decision models. Policymakers pursuing Fit-for-55 standards and operators looking to create robust, low-carbon supply chains are given implications.

1 INTRODUCTION

The foundation of multimodal logistics in the Mediterranean basin is made up of roll-on/roll-off (Ro-Ro) transportation networks, which connect Europe, North Africa, and the Middle East in a smooth and adaptable network of freight flow. Ro-Ro transport is particularly effective for time-sensitive and short-to-medium distance transactions because of its primary operational benefit, which is the capacity to enable wheeled cargo to be pushed on and off vessels without requiring considerable cargo handling (Christodoulou & Kappelin, 2020). The Mediterranean Ro-Ro corridor is becoming more than just a logistics route as regional trade volumes continue to rise; it is also becoming an essential component of Europe's efforts to achieve resilience, economic solidarity, and sustainable development (Zis et al., 2019)..

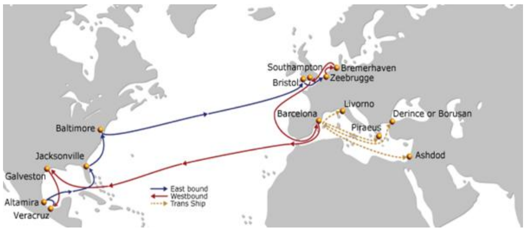

Figure 1. Mediterranean Ro-Ro shipping routes connecting major ports across Europe, North Africa, and the Middle East. The map illustrates the extensive network of established routes that facilitate regional trade and logistics integration. Source: "K" Line Car Carrier RoRo North America East Coast - Europe & Mediterranean Service Route Map (2024)

Despite its fundamental importance, it is a turning point in the sector. Realizing the full construction potential of Ro-Ro is hindered by complex frameworks, increasing focal concerns and inadequate infrastructure, as a growing body of literature shows (Psaraftis, 2016; Russo et al., 2023). Congested port access roads, lack of digitalization and extended restrictions to old terminals combine to create inefficiencies, increase carbon emissions and reduce service resilience (Karountzos, 2024). The International Maritime Organization's (IMO) decarbonisation target and the EU's 'Highways of the Sea' project act both simplified and restrictive, forcing change and raising the bar for technical competence (López-Navarro, 2014; IMO, 2023).

This study explores two converging paths to address emergent products for Mediterranean Ro-Ro assembly: (i) new, evidence-based Ro-Ro routes to fill in existing connectivity gaps, and (ii) the creation of a thorough evaluation framework that uses Multi-Criteria Decision Making (MCDM) techniques, more specifically the Analytic Hierarchy Process (AHP), to evaluate and optimise both proposed and existing networks.

1.1 *Ro-Ro Networks' Strategic Significance in the Mediterranean*

Due to its flexibility, quicker delivery times, and lower transfer costs, Ro-Ro transportation gives regional logistics a competitive edge over container-based transportation (Camarero Orive et al., 2022). The Mediterranean is home to several famous Ro-Ro corridors, such as those that link Marseille and Tunis, Barcelona and Tripoli, and Genoa and Tangier. Ship frequencies can range from daily sailings to weekly schedules, contingent on seasonal demand (Demirel & Demir, 2024). Large chokepoints like the Strait of Gibraltar and the Bosphorus act as both geopolitical flashpoints and capacity limiters.

Figure 2. Types of maritime transport in the Mediterranean, highlighting the distinct role of Ro-Ro shipping alongside dry bulk, liquid bulk, and container transport. This classification illustrates the diverse maritime logistics ecosystem in which Ro-Ro operations function. Source: Gattuso, D., Cassone, G.C. & Pellicanò, D.S. (2022). Assessment of freight traffic flows and harmful emissions in euro-mediterranean context: scenario analyses based on a gravity model. Journal of Shipping and Trade, 7(13).

In addition, trade policies, cultural influences and economic asymmetries intersect in the Mediterranean. Harmonization efforts in customs procedures, port state controls and emissions reporting are complicated by the fragmentation of regulatory frameworks between EU member states and non-EU countries (Panagakos et al., 2019; Paraskevadakis and Ifeoluwa, 2022). These inequalities can cause prices to rise and maritime transport to become less attractive, which could lead to a shift of goods to less environmentally friendly land options..

1.2 *Sustainability Mandates and Environmental Integration*

Ro-Ro operators are subject to strict fuel quality standards and emission caps because the IMO has designated the Mediterranean as a Sulphur Emission Control Area (SECA) (IMO, 2023). This is complemented by the EU's Fit for 55 packages, which call for a 55% reduction in greenhouse gas emissions by 2030 compared to 1990 levels. As a result, Ro-Ro operators must now make investments in shore-side electricity, hybrid propulsion, and low-sulfur fuels (Zis et al., 2019; Santos & Santos, 2024). However, given shifting fuel markets and shifting political landscapes, compliance costs are high, particularly for small-to-medium shipping lines, and the return on investment is uncertain (Belcore et al., 2023).

By including lifecycle emissions and fuel efficiency in the decision-making matrix, the paper incorporates these mandates into the framework for route evaluation. This allows for a comprehensive sustainability assessment for route prioritisation by placing environmental metrics on par with operational and economic parameters (López-Navarro, 2020).

1.3 *Port Performance, Intermodality, and Infrastructure*

An ongoing weakness in the Mediterranean Ro-Ro ecosystem is infrastructure. Several ports suffer from antiquated ICT systems, lack dedicated Ro-Ro ramps, and are congested as a result of poor hinterland connectivity (Morales Fusco, 2016). This hinders multimodal integration, especially with rail and inland waterways, as well as loading/unloading efficiency. By providing incentives for integrated transport planning that synchronizes land-based and maritime flows, Camarero Orive et al. (2022) hope to break this impasse with their 4R strategy: Road, Rail, River, and Ro-Ro.

Terminal competitiveness also varies greatly. Some ports in North Africa experience delays because of political unrest and bureaucratic inertia, while ports like Valencia and Trieste score highly on digitalization and customs performance (Russo et al., 2023; Psaraftis, 2016). The research maps capacity disparities and identifies "opportunity hubs" where targeted investments could result in significant throughput gains by using a geospatial analysis of more than 30 Mediterranean Ro-Ro terminals (Karountzos, 2024).

1.4 *Theoretical Framework and Methodological Rigor*

The Analytic Hierarchy Process (AHP), a validated MCDM technique that uses structured pairwise comparisons to capture expert judgement, forms the methodological basis of this study (Saaty, 1980). AHP provides a strong tool for prioritising routes and investments by giving weights to factors like fuel cost, emissions, port efficiency, regulatory alignment, and freight demand elasticity (Zis et al., 2019; Psaraftis, 2016).

Delphi-derived weights will be used to gather stakeholder input for the study, and a scenario-based approach will be used to validate the results. To test the resilience of suggested Ro-Ro strategies, these scenarios will include changes in fuel prices, carbon taxes, and geopolitical upheavals (López-Navarro, 2020; Raza, 2020). The goal of this multifaceted approach is to develop an evidence-based and flexible decision-support framework.

1.5 *Proposed Routes and Strategic Recommendations*

Three interesting new Ro-Ro-Rs, according to preliminary simulations, are Alexandria–Thessaloniki to boost Euro-Egyptian supply chains, Algiers–Barcelona to increase North African exports, and Beirut–Piraeus as a conflict-resilient alternative to overland Levant trade (Demirel & Demir, 2024; Belcore et al., 2023). Latent demand analysis, congestion measures, and their possible support of EU-African trade corridors helped to guide the choice of these paths.

Based on estimates by Morales Fusco (2016) and Christodoulou & Woxenius (2020), the final framework will also advise on which ports merit capacity expansions, which regulatory alignments offer the best economic return, and how digitalisation might cut turnaround times by over 20%.

Mediterranean Ro-Ro transport finds itself at a crossroads. Although its operational flexibility and geographical benefits are still indisputable, the industry now has to match the demands of the twenty-first century including environmental stewardship, digitalisation, and policy consistency. This paper offers not only fresh strategic paths but also a thorough, multi-criteria framework for assessing their viability, resilience, and sustainability, so helping to facilitate that change. From legislators and port authorities to shipping operators, the results seek to serve a wide spectrum of stakeholders by offering actionable intelligence grounded in multidisciplinary research and empirical analysis.

Research Questions

- When evaluated using expert consensus, which operational, infrastructure, and environmental factors most significantly affect the competitiveness of Mediterranean Ro-Ro routes?
- Where do important gaps show and how does the spatial distribution of AIS-derived traffic density match AHP-based priority weights?
- While minimising congestion in current corridors, what new or modified Ro-Ro-paths can maximise throughput and decarbonisation potential?

2 LITERATURE REVIEW

2.1 *Historical and Conceptual Foundations of Ro-Ro Transport*

Along with containerisation, Ro-Ro transportation developed following World War II to allow effective handling of wheeled goods. Originally motivated by military logistics, by the 1960s it was becoming commercially important in Europe. Notteboom & Rodrigue, 2009; Levinson, 2006; key academics underlined how it developed within intermodalism and corridor logistics. Originally developed in Northern Europe during the 1980s and 1990s, the idea then migrated to Mediterranean environments. Along with the creation of port logistics clusters (Ferrari et al., 2015), which support Ro-Ro as both a transport solution and regional economic enabler, investments and policy support were absolutely vital.

2.2 *Mediterranean Context for Ro-Ro Transportation*

Crucially important for Mediterranean trade, Ro-Ro links Europe with North Africa and Asia. Port upgrades—such as those at Valencia, Koper, Piraeus—have been supported by EU projects including Motorways of the Sea (MoS). Master plans and environmental incentives help Ro-Ro to be promoted by national policies in Italy and Turkey. While smaller ports like Igoumenitsa have scaled up with EU support, key ports including Trieste and Valencia highlight intermodal integration. But North African ports lag behind because of digital and infrastructure gaps, so limiting complete regional integration.

2.3 *Operational and Logistical Benefits*

Rapid turnaround, less handling, and flawless intermodal transfers are just a few of Ro-Ro's offerings. Ports like Zeebrugge and Marseille have maximised logistics with technologies including RFID, artificial intelligence-based yard systems, and blockchain customs. Mediterranean hubs like Trieste and Koper improve JIT logistics by linking straight to rail. For developing countries, Ro-Ro also offers flexible cargo configurations, better space use (Brønmo et al., 2007), and less infrastructure investment.

2.4 *Obstacles and Restraints*

Geopolitical concerns (Libya, Syria), fractured maritime security, and infrastructure differences—especially between Northern and Southern Mediterranean ports—threatens Ro-Ro networks. While many ports lack shore power or green fuel alternatives, environmental rules—e.g., IMO 2020, Fit-for-55—cause great compliance costs. Cross-border flows suffer from customs inefficiencies and poor digital integration. One of the main bottlenecks still is stakeholders' coordination, which reduces the Ro-Ro system's resilience.

2.5 *Ro-Ro and Eco-friendly Maritime Transportation*

The targets of EU decarbonisation depend much on Ro-Ro. Gradually taking front stage are LNG-fueled vessels (Grimaldi, DFDS), shore power systems (Barcelona, Marseille), and hybrid propulsion. Port projects at Valencia and Piraeus highlight environmentally friendly port operations. Smaller ports still suffer with unclear rules, retrofitting expenses, and unequal access to green fuels. Scalable sustainability calls both coordinated investments and harmonised policies.

2.6 *Overview of Existing Ro-Ro Routes in the Mediterranean*

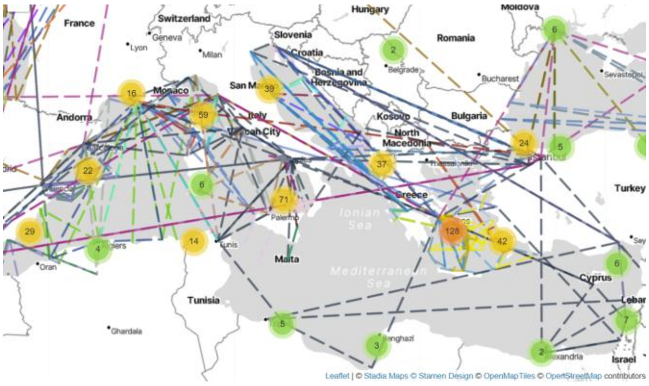

Figure 3. Overview of Exiting Ro-Ro Routes in the Mediterranean

For goods and passengers, the Mediterranean supports a rich web of Ro-Ro and Ro-Pax services. Major corridors link Spain (Barcelona, Valencia), France (Marseille), Italy (Trieste, Genoa), Türkiye (Pendik, Ambarlı, Çeşme), Greece (Igoumenitsa), and North Africa (Tunis, Algiers, Tanger Med.). Using competitive port facilities—intermodal links, automation, and regulatory incentives—operators including DFDS, Grimaldi, GNV, and Baleària maximise route performance. For effective and environmentally friendly marine logistics, a coherent plan combining several networks is still absolutely necessary.

Table 1 shows the comparison overview of existing roro routes and their unique advantages.

Table 1 The Comparison Overview of Existing RoRo Routes and their Unique Advantages

Country	Port	Key Operators & Routes	Unique Advantages
Spain	Barcelona	Grimaldi Lines: Barcelona ⇄ Tanger Med; GNV: Barcelona ⇄ Civitavecchia; Baleària: Barcelona ⇄ Palma de Mallorca	Deep-water terminals; ZAL intermodal link; Customs pre-clearance; High annual volume
Spain	Valencia	GNV: Valencia ⇄ Tunis; Grimaldi Lines: Valencia ⇄ Mostaganem	Modern RTGs and shuttle trains; Fast rail to Madrid; Competitive port incentives
Spain	Algeciras	Baleària: Algeciras ⇄ Tanger Med; Acciona Trasmed: Huelva ⇄ Tanger Med	24/7 multi-berth operations; Free-trade zone & bonded warehouses; Proximity to Gibraltar
France	Marseille	Corsica Ferries: Marseille ⇄ Bastia; GNV: Marseille ⇄ Algiers, ⇄ Tunis	EU funding; Direct motorway to Italy; Port Community System
France	Sète	Grimaldi Lines: Sète ⇄ Tanger Med; Baleària: Sète ⇄ Nador	Lower congestion; Deep-water berths; Integrated logistics park; Attractive fees
Italy	Genoa	GNV: Genoa ⇄ Palermo; Grimaldi Lines: Genoa ⇄ Catania	>2 M lane-metres capacity; 24-hour service; Excellent rail links; LNG bunkering
Italy	Livorno	Corsica Ferries: Livorno ⇄ Bastia; Moby Lines: Livorno ⇄ Golfo Aranci	Direct rail sidings; Surge staffing for peaks; Lower off-peak dues
Italy	Civitavecchia	Grimaldi Lines: Civitavecchia ⇄ Tanger Med; GNV: Civitavecchia ⇄ Palermo	'Sea door of Rome'; Electrified cranes; Refrigerated lanes; Short land-bridge
Italy	Naples	Grimaldi Lines: Naples ⇄ Palermo	Central hub; Container-Ro-Ro integration; Deep draft
Italy	Salerno	SNAV: Salerno ⇄ Palermo	Off-season incentives; Close to Campania industrial zone
Italy	Ancona	ANEK Lines: Ancona ⇄ Patras; Superfast Ferries: Ancona ⇄ Igoumenitsa	Drive-through berths; Port-apron rail link; Digital manifests
Italy	Venice (Marghera)	Grimaldi Lines: Venice ⇄ Patras	Freight-only terminal; Intermodal depot; Environmental controls
Italy	Trieste	DFDS, Grimaldi Lines: Trieste ⇄ Türkiye, Balkans, Central Europe	3 M+ lane-metres; TEN-T corridor; Direct rail; Bonded warehousing
Greece	Patras	ANEK Lines: Patras ⇄ Ancona; Grimaldi Lines: Patras ⇄ Venice	24 hr ops; Short gate-to-vessel distance; E55/E65 road links
Greece	Igoumenitsa	Superfast Ferries: Igoumenitsa ⇄ Ancona; ANEK Lines: Igoumenitsa ⇄ Bari	Fastest crossings; Doubled berths; On-site customs; Albanian corridor
Greece	Piraeus	Minoan Lines: Piraeus ⇄ Heraklion; ANEK/Superfast: Piraeus ⇄ Chania	Massive hinterland rail; Single-window customs; Passenger-freight synergy
Turkey	Mersin	Grimaldi Lines: Mersin ⇄ Piraeus; ANEK Lines: Mersin ⇄ Thessaloniki	Three Ro-Ro terminals; O-51/O-21 motorways; Refrigerated & livestock lanes
Turkey	İzmir (Alsancak)	ANEK Lines: İzmir ⇄ Piraeus; DFDS: İzmir ⇄ Sète	Logistics park; EU grants; O-30 ring road
Turkey	Çeşme	Local ferries: Çeşme ⇄ Chios	Compact ramp ops; Minimal congestion; Tourism synergy; Direct highway
Turkey	Pendik (Istanbul)	DFDS: Pendik ⇄ Trieste	Deep-water quay; O-4 motorway; Large yard; Bosphorus access
Turkey	Ambarlı (Istanbul)	DFDS: Ambarlı ⇄ Trieste	European-side access; Bonded dry port; Rail link underway
Turkey	Martaş (Tekirdağ)	DFDS: Martaş ⇄ Trieste	Shortest sea leg; Drive-through berths; Lower dues; Highway access
Turkey	Yalova	DFDS: Yalova ⇄ Trieste & Sète	Inner-sea shelter; Quick ramps; Trailer storage; Feeder to Pendik
Malta	Gemlik	DFDS and others: Gemlik ⇄ Trieste	Deep draft; Bursa rail; Full logistics services
Tunisia	Valletta	Virtu Ferries: Valletta ⇄ Pozzallo	Central location; Park-and-ride; Lower dues

Strategically placed ports on the Mediterranean's Ro-Ro and ferry network each use geography, infrastructure, and policy incentives to draw cargo flows. Key hubs comprise Spain's intermodal ports (Barcelona, Valencia), France's EU-supported corridors (Marseille, Sète), Italy's axis ports (Genoa, Trieste, Civitavecchia), Greece's gateway ports (Piraeus, Patras, Igoumenitsa), and Türkiye's seven-terminal network connecting Europe and North Africa. Malta and Tunisia enhance this with deliberate trans-Mediterranean programs.

Ports investing in alternative fuels, digital systems, and rail links will lead in competitiveness as decarbonisation, digitalisation, and resilience take front stage. Maximising service planning and future investments depends on an awareness of the strengths of every terminal.

2.7 *Port Capacities and Infrastructure Reversibility*

Mediterranean logistics revolves mostly on Ro-Ro transportation. Thanks to investments in digital infrastructure, ports including Trieste, İzmir, and Mersin lead in capacity and intermodal connectivity. Smart Ro-Ro operations are best shown by Tanger Med in Morocco. Barcelona and Valencia combine strong hinterland links with container and Ro-Ro flows. On the other hand, infrastructure and efficiency restrictions apply in Libya, Albania, some areas of Egypt and Algeria.

2.8 *Different Kinds of Cargo Carried*

Mostly between Türkiye, Italy, and France, Ro-Ro cargo consists of unaccompanied trailers and passenger cars. Seasonal peaks in tourism and agriculture impact volumes. Growing project cargo (such as construction equipment) calls for ports with advanced ramps and side-loading capability like Mersin and Valencia.

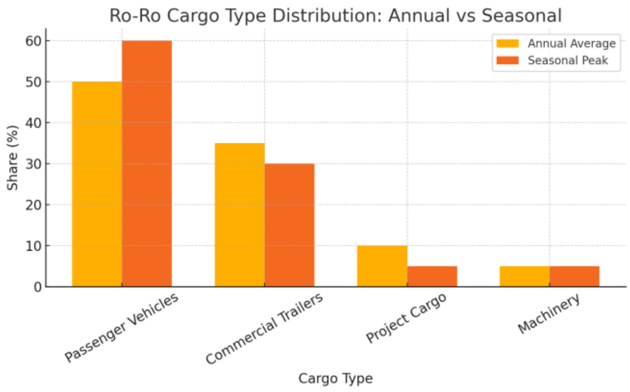

Figure 4. Cargo Share Chart: Annual vs Seasonal Breakdown source: Eurostat

2.9 *Intermodality and Connectivity*

Top-performing ports like Trieste and Valencia strengthen delivery times by integrating dry ports and rail lines, so lowering emissions. Such corridors are supported by EU Motorways of the Sea. Still lacking dry ports and rail connections, areas like Algeria and Libya therefore depend more on road transport.

2.10 *Operational Bottlenecks*

Key challenges include seasonal congestion, labor strikes, and customs inefficiencies—particularly in North African ports. Many older ports suffer from shallow berths and lack vehicle staging areas, affecting

2.11 *Local Reversals and Underutilisation*

Often resulting from political or economic instability, high-capacity corridors (e.g., Italy–Spain) contrast with underused routes (e.g., France–Algeria). Though strategically located, ports including Damietta, Igoumenitsa, and Oran are underused. Optimising their possible needs focused policies and coordinated investments.

2.12 *Port Competitiveness: Foundation of Literature*

Operating efficiency, connectivity, governance, and digitalisation define port competitiveness. Research over more than 20 years reveals important elements including port costs, service quality, customs efficiency, ICT use, and smart port readiness. Recent research underline models with integration rather than cost-centric ones.

Table 2 The port competitiveness factors found in the literature.

Author(s)	Competitiveness Factors Identified
French	Terminal facilities, tariffs, port congestion, connectivity, hinterland economy, national economic status, trade policy
Collison	Ship waiting time, port schedule confidence, service capacity
Brooks	Port costs, vessel call frequency, port loyalty, cargo damage
Murphy et al.	Handling large/odd cargo, claims handling, special equipment, damage, delivery
Haezendonck et al.	Functional port activities (foreland, internal, hinterland), governance, demand conditions
Tongzon and Heng	Cargo handling, operational efficiency, product differentiation, channel depth
Yeo et al.	Logistics cost, hinterland condition, availability, service convenience
Yuen et al.	Port location, services, operator quality, ICT systems
Dyck and Ismael	Costs, infrastructure, political stability, cargo volume
Parola et al.	Infrastructure, connectivity, hinterland access, site conditions
Hales et al.	Customer-facing: service, fees, cargo volume. Investor-facing: law, resources, structure
Omoke & Onwuegbuchunam	Turnaround time, crane efficiency, cargo space, pre-berthing time
Mdanat et al. (2024)	Logistic performance, digital infrastructure, ease of doing business, trade facilitation
González-Cancelas & Molina Serrano (2020)	Digitalization in ports, productivity, communication systems, visibility
Jugović et al. (2022)	Environmental policies, stakeholder alignment, green governance
Yang & Hsieh (2024)	Smart port digitalization, resilience post-COVID, automation
Tijan et al. (2022)	Terminal efficiency, digital logistics infrastructure, throughput optimization
Huang et al. (2022)	Hinterland integration, urban connectivity, technological readiness
Castillo-Manzano et al. (2009)	Regional governance, pricing systems, cost evaluation methods
Kaliszewski et al. (2020)	Shipping line preferences, global network integration, infrastructure readiness
Luo et al. (2022)	Port cooperation vs. competition, policy harmonization, inter-port dynamics
Tovar et al. (2015)	Spatial integration, port connectivity, regional competitiveness

Terminal-level determinants and AHP criteria

Applied in AHP models, key competitiveness criteria comprise: market offers (fees, service scope); resources (intermodal links, capacity); management (partnerships, labour stability).

- Environmental harmony
- Frequency in nautical design: accessibility
- External circumstances (personal preferences, policy encouragement)

These elements enable benchmarking and assessment of Ro-Ro terminals. Using expert surveys and consistency ratios, AHP applications including Karountzos (2024) confirm their efficacy.

Competitiveness Criteria for Terminal Level AHP Modelling

Table 3 Terminal-Level Competitiveness Criteria for AHP Modeling

No	Competitiveness Factors	Area of Competitiveness
1	Ro-Ro terminal fees, vehicle lane charges, and rebate policies	Terminal market offerings
2	Scope of Ro-Ro terminal services (e.g., pre-check-in, vehicle storage, logistics handling)	Terminal market offerings
3	Ro-Ro service quality (loading/unloading speed, operational safety, digital booking, eco-efficiency)	Terminal market offerings
4	Integration of Ro-Ro terminal with port community systems (customs, vehicle inspection, real-time updates)	Terminal resources
5	Capacity to handle high-frequency Ro-Ro vessels and multiple ship calls per day	Terminal resources
6	Availability of intermodal links (road/train ramps for vehicle discharge, ferry-bus logistics)	Terminal resources
7	Ownership structure of Ro-Ro terminals (public/private mix, operator autonomy)	Terminal management
8	Strategic partnerships with shipping lines, ferry operators, and logistics firms	Terminal management
9	Flexibility in adapting terminal layout to accommodate new Ro-Ro ship designs	Terminal management
10	Stability in terminal labor-management relations and absence of strikes	Terminal management
11	Environmental practices (shore power availability, noise control, vehicle emissions management)	Environmental compliance
12	Reputation of the Ro-Ro terminal among transport companies and end users	Terminal image and branding
13	Nautical accessibility (ramp design, berth depth, manoeuvrability)	Terminal accessibility
14	Frequency and variety of Ro-Ro services offered (passenger-freight mix, cross-border service)	Terminal accessibility
15	Customs and border inspection efficiency for Ro-Ro cargo/passenger flows	External business environment
16	Government policies supporting Ro-Ro infrastructure and hinterland logistics	External business environment

Maritime transport planning is now largely based on multi-criteria decision making (MCDM) techniques. Among these, the Analytic Hierarchy Process (AHP), first proposed by Saaty (1980), has shown great value in organizing expert opinions to derive quantitative priorities from qualitative inputs. Its use in maritime environments is quite common; for example, Notteboom, Pallis, and Rodrigue (2022) used AHP to evaluate port competitiveness, while Karahalios (2017) applied AHP in the evaluation of environmental management strategies for ballast water treatment systems.

In parallel, Geographic Information Systems (GIS) have become indispensable tools for network optimization and spatial analysis in marine research. Providing a strong basis for environmental impact analysis, Trozzi, Vaccaro and Nicolo (1995) developed high-density emission inventories for ships operating in the Mediterranean Sea using GIS methods. To assess the risks of water quality degradation in port areas, Grifoll et al.(2020) similarly combined GIS with hydrodynamic modelling, so demonstrating the ability of the method for sophisticated, spatially explicit modelling.

Recent research highlight the synergy between MCDM methods including AHP and GIS tools, so facilitating a more complete knowledge of marine logistics systems.The evaluation and development of short sea shipping and Ro-Ro shipping networks depend on the visualization and analysis of complex spatial relationships that this integration helps.

Environmental sustainability has also come to the fore in maritime design. The industry is moving towards more sustainable practices with the European Union's Green Deal and the International Maritime Organization's (IMO, 2018) first strategy on greenhouse gas (GHG) reduction. In this context, Green Sea Corridors developed by Psaraftis (2019) provide a strategic framework for the creation of environmentally friendly sea routes.

This paradigm balances helping reduce emissions with the operational and commercial needs of the maritime industry.Taken together, these methodological tools – AHP for structured prioritization, GIS for spatial modelling, and sustainability frameworks such as Green Transport Corridors – form the basis of the analytical approach to the optimization of Ro-Ro networks in the Mediterranean basin.

Conceptual Map of Key Literature Streams

Theme	Representative Authors	Identified Gap
Port competitiveness via MCDM	Notteboom et al. 2013; Ferrari et al. 2011	Rare integration with spatial traffic analytics
Sustainability & decarbonisation	Psaraftis 2019; IMO 2018	Limited route-specific mitigation strategies
Network optimisation	Rodrigue 2006; Acciaro et al. 2023	Fragmented focus on individual ports over corridor systems

3 METHODOLOGY

This work uses a multidisciplinary, mixed-methods approach combining quantitative analysis with qualitative assessment strategies in order to reach the research objectives. The approach consists in three separate phases:

3.1 *Phase 1: AHP, factor identification and prioritising*

1. The first phase sought to pinpoint and rank elements influencing Ro-Ro terminal competitiveness using the Analytic Hierarchy Process The method consisted in:
   One can identify factors by: Sixteen competitiveness elements were found by means of literature review and expert consultation, classified into four dimensions: operational, economic, technological, environmental.
2. Design for Expert Survey: Twenty professionals from port authorities, shipping lines, and academia received an expert survey with 55 AHP-based items. Consistency ratios were computed by means of Saaty's 1–9 scale for pairwise comparisons. Aggregate weightings using geometric means

found the most important competitiveness criteria for Mediterranean Ro-Ro operations.

Table 4. AHP scale of importance for pairwise comparisons.

Factor_ID	Factor_Name	Description	Weight
F1	Ro-Ro terminal fees, vehicle lane charges, and rebate policies	Economic factor related to the cost structure of using Ro-Ro terminals, including fees for vehicle lanes and available rebate policies	0.0663
F2	Scope of Ro-Ro terminal services	Range of services offered at terminals including pre-check-in, vehicle storage, and logistics handling capabilities	0.0652
F3	Ro-Ro service quality	Operational quality metrics including loading/unloading speed, operational safety, digital booking systems, and eco-efficiency	0.0609
F4	Integration with port community systems	Digital integration with customs, vehicle inspection, and real-time updates systems	0.0907
F5	Capacity to handle high-frequency Ro-Ro vessels	Terminal capacity to accommodate multiple ship calls per day and high-frequency vessel operations	0.0928
F6	Availability of intermodal links	Infrastructure for multimodal connections including road/train ramps for vehicle discharge and ferry-bus logistics	0.0917
F7	Ownership structure of Ro-Ro terminals	Governance factor related to public/private ownership mix and operator autonomy	0.036
F8	Strategic partnerships	Collaborative arrangements with shipping lines, ferry operators, and logistics firms	0.0423
F9	Flexibility in terminal layout adaptation	Ability to modify terminal configuration to accommodate new Ro-Ro ship designs	0.0358
F10	Labor-management relations stability	Workforce stability factors including labor relations and absence of strikes	0.0359
F11	Environmental practices	Sustainability measures including shore power availability, noise control, and vehicle emissions management	0.0899
F12	Terminal reputation	Market perception of the terminal among transport companies and end users	0.0385
F13	Nautical accessibility	Physical access factors including ramp design, berth depth, and vessel maneuverability	0.0629
F14	Frequency and variety of Ro-Ro services	Service diversity including passenger-freight mix and cross-border service options	0.0657
F15	Customs and border inspection efficiency	Speed and effectiveness of customs clearance and border inspection for Ro-Ro cargo/passenger flows	0.0664
F16	Government policy support	Policy environment supporting Ro-Ro infrastructure development and hinterland logistics	0.059

3. 25 experts in all—port authorities (28%), shipping operators (24%), logistics providers (20%), academic researchers (16%), and policy advisers (12%), assembled on a panel Average marine logistics experience among participants was 15.3 years.
4. Expert opinions were gathered by means of online polls and organised interviews. Consistency Ratio (CR) approach allowed one to build and examine individual pairwise comparison matrices for consistency. Experts were consulted again for explanation on judgements with CR > 0.1.
5. Individual assessments were aggregated into a consolidated pairwise comparison matrix using the geometric mean method. The main eigenvector of this matrix was calculated to derive the last priority weights for every 16 factor.

The Analytic Hierarchy Process (AHP) involves constructing a pairwise comparison matrix, denoted as:

1.

$$A = \left[a_{ij} \right]_{nxn} = \begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ 1/a_{12} & 1 & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ 1/a_{1n} & 1/a_{22} & \cdots & 1 \end{bmatrix}$$

Each element a_{ij} represents the relative importance of criterion i to criterion j.

To derive the priority vector $w = [w_1, w_2, ..., w_n]$ from the matrix, the geometric mean method is often used:

2.

$$w_i = \frac{\left(\prod_{j=1}^{n} a_{ij} \right)^{1/n}}{\sum_{i=1}^{n} \left(\prod_{j=1}^{n} a_{ij} \right)^{1/n}}$$

This formula computes each weight w_i as the normalized geometric mean of row i.

To evaluate the consistency of the pairwise comparisons, the Consistency Ratio (CR) is calculated:

3.

$$CR = \frac{CI}{RI} = \frac{\lambda_{\max} - n}{(n-1) \cdot RI}$$

where λ_{max} is the maximum eigenvalue of the matrix A, n is the number of criteria, CI is the consistency index, and RI is the random index based on matrix size (Saaty, 1980).

3.2 *Phase 2: Gap identification and current network analysis*

Using information from port authorities, shipping lines, and scholarly sources, this phase mapped the current Ro-Ro network over significant Mediterranean ports. Top-weighted AHP factors—e.g., capacity, intermodal connectivity, digital systems, and environmental practices—were compared qualitatively. This exposed operational limitations, infrastructure gaps, and lost possibilities for better trade integration and service coverage.

3.3 *Phase 3: Route proposition and evaluation framework*

The results led to the proposal of new strategic routes: Ambarlı–Trieste–Marseille and Damietta–Patras–Trieste. Incorporating AHP-derived factor weights, operational metrics (e.g., transit times, efficiency), economic viability indicators, interimodal integration potential, compliance with EU/IMO environmental standards, a multi-criteria evaluation framework was developed.

Implementation comprises GIS-based spatial modelling, route feasibility, and environmental impact visualisation.

3.4 *Data References*

3.4.1 *Main data*

- Expert Survey for AHP: Designed with 55-item questionnaires emphasising pairwise comparisons of competitiveness factors, 20 marine experts were surveyed.
- General Industry Survey: To measure operational factor relevance, distributed to 89 Ro-Ro operators, goods forwarders, and logistics providers all around the Mediterranean.

3.4.2 *Supporting Information*

Strategic and operational data from authorities and Ro-Ro carriers—e.g., DFDS, Grimaldi, GNV—port and operator reports.

- Industry Studies: Alphaliner's forecasts and research from sources including Drewry
- Geospatial Data: From European Transport Maps and AIS systems, route and traffic maps
- Academic Literature:Peer-reviewed materials on Ro-Ro logistics, port performance, and intermodal networks abound in academic literature.
- Policy Frameworks: EU and IMO papers on decarbonisation, sustainable transportation, and green shipping corridors form policy frameworks.

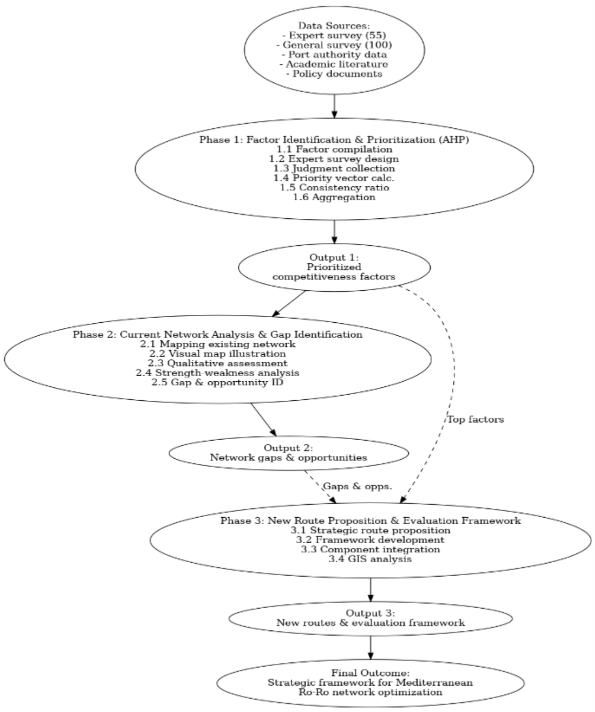

Figure 5. Methodology flowchart

Figure 5 illustrates this triangulated data approach ensures robust analytical grounding for evaluating Mediterranean Ro-Ro network optimization.

4 RESULTS

The main results of the application of the AHP to prioritise Ro-Ro competitiveness elements, the GIS study of the present Mediterranean Ro-Ro network, and the assessment of suggested new paths are presented in this part.

Table 5. Prioritized Ro-Ro Competitiveness Factors

Rank	Factor	Weight
1	F5 – Capacity to handle high-frequency Ro-Ro vessels	0.0928
2	F6 – Availability of intermodal links	0.0917
3	F4 – Integration with port community systems	0.0907
4	F11 – Environmental practices	0.0899
5	F1 – Ro-Ro terminal fees and charges	0.0876
6	F14 – Frequency and variety of Ro-Ro services	0.0865
7	F3 – Ro-Ro service quality and reliability	0.0854
8	F9 – Terminal security measures	0.0843

The AHP analysis yielded a clear hierarchy of competitiveness factors for Mediterranean Ro-Ro terminals. Table I presents the top eight factors with their normalized weights.

Table 6. Top Prioritized Ro-Ro Competitiveness Factors

Rank	Factor ID	Factor	Weight
1	F5	Capacity to handle high-frequency Ro-Ro vessels	0.0928
2	F6	Availability of intermodal links	0.0917
3	F4	Integration with port community systems	0.0907
4	F11	Environmental practices	0.0899
5	F1	Ro-Ro terminal fees and charges	0.0875
6	F14	Frequency and variety of Ro-Ro services	0.0862
7	F3	Ro-Ro service quality and reliability	0.0854
8	F9	Terminal security measures	0.0843

With a consistency ratio of 0.032—much below the 0.1 cutoff—the aggregated judgement matrix displayed great consistency in expert assessments. The results show a change in industry priorities towards operational efficiency and integration as operational factors (capacity, intermodal links) and technological factors (digital integration) rank somewhat higher than economic factors (fees and charges).

Environmental practices (F11) came fourth, which reflects the rising relevance of sustainability in maritime logistics. This marks a notable change from earlier research in which environmental elements usually scored less in assessments of competitiveness.

The GIS study exposed several important trends and holes in the present Mediterranean Ro-Ro-Network:

To give a whole picture of the Mediterranean Ro-Ro transport system, this integrated gap study compiles data from the Central and Eastern Mediterranean areas. This study reveals important misalignments between current network performance and strategic priorities over the whole Mediterranean basin by aggregating Geographic Information System (GIS) marine traffic density data with Analytic Hierarchy Process (AHP) priority findings.

The analysis covers the following regions:

– Central Mediterranean; Sicily Channel, Tyrrhenian Sea;
– Eastern Mediterranean; Aegean Sea, Levantine Basin
– Adriatic Sea
– Northeastern African coastlines (Egypt, Libya)
– sea of Marmara and Turkish Straits

This all-encompassing approach helps to identify basin-wide trends, regional differences, and strategic chances for network optimisation supporting the study goals of creating new marine routes improving regional trade and environmental impact. Using a multi-layered technique, the integrated study:

1. GIS Analysis: Examining maritime traffic density heat maps (September 2024) across the whole Mediterranean will help one to find established shipping routes, congestion hotspots, and traffic distribution patterns..
2. AHP Prioritising: Using expert-validated weights for sixteen competitiveness criteria, paying especially attention to the top four priorities::
   – F5: Capacity to handle high-frequency Ro-Ro vessels (Weight: 0.0928)
   – F6: Availability of intermodal links (Weight: 0.0917)
   – F4: Integration with port community systems (Weight: 0.0907)
   – F11: Environmental practices (Weight: 0.0899)
3. Gap Mapping: Identification of specific misalignments between current network performance and strategic priorities, categorized by:
   – Severity (Critical, High, Moderate, Low)
   – Type (Infrastructural, Operational, Digital, Environmental)
   – Geographic Scope (Region, Corridor, Port)
4. Strategic Opportunity Assessment: Evaluation of potential interventions and route developments to address identified gaps.

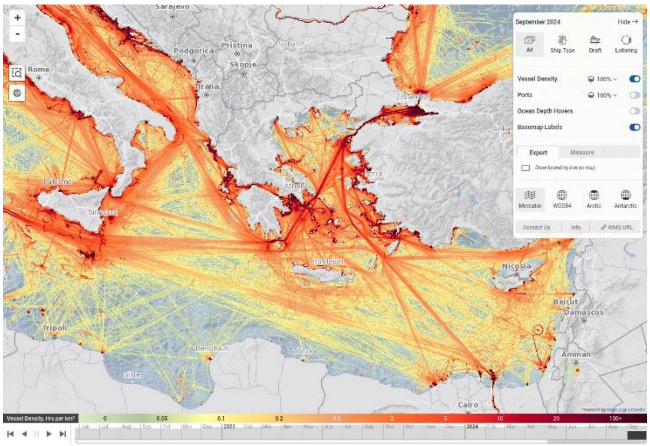

Figure 6. Heat map of maritime traffic density in the Eastern Mediterranean region, September 2024. The color gradient from yellow (low) to dark red (high) indicates vessel traffic intensity measured in hours per square kilometer. Source: Global Maritime Traffic Density Service (GMTDS), 2024

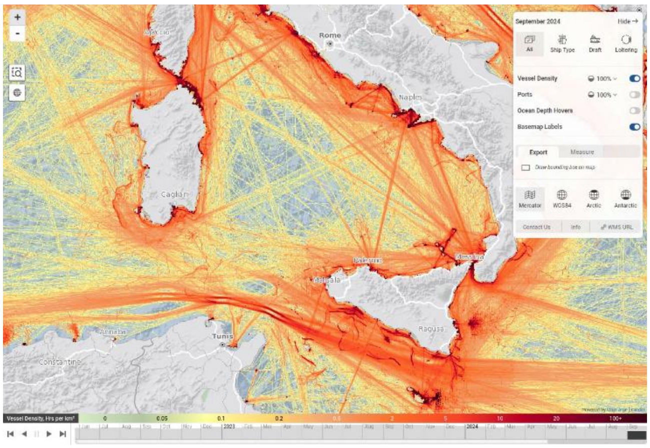

Figure 7. Heat map of maritime traffic density in the Central Mediterranean region, September 2024. The color gradient from yellow (low) to dark red (high) indicates vessel traffic intensity measured in hours per square kilometer. Source: Global Maritime Traffic Density Service (GMTDS), 2024

Basin-Wide Gap Analysis: Critical Misalignments

The integration of Central and Eastern Mediterranean analyses reveals several basin-wide patterns of misalignment between current network performance and AHP-prioritized competitiveness factors:

Capacity Constraints at Strategic Chokepoints (F5 - Weight: 0.0928)

The highest-priority AHP factor (Capacity) faces critical constraints at multiple strategic chokepoints across the Mediterranean:

1. Turkish Straits Crisis: The most severe capacity constraint in the entire Mediterranean, with extreme congestion (dark red) in the Bosporus and Dardanelles Straits creating a critical bottleneck for all vessel movements between the Mediterranean and Black Sea.
   – Severity: Critical
   – Impact: Affects all vessel movements between Mediterranean and Black Sea, including potential Ro-Ro services
   – Geographic Scope: Bosporus and Dardanelles Straits, Sea of Marmara
2. Messina Strait Bottleneck: The second most severe capacity constraint, with extreme congestion (dark red) in the narrow passage between Sicily and mainland Italy creating a critical bottleneck affecting multiple major Ro-Ro routes.
   – Severity: Critical
   – Impact: Affects all vessel movements between Eastern and Western Mediterranean via the Tyrrhenian Sea
   – Geographic Scope: Messina Strait and approaches
3. Piraeus Hub Congestion: High traffic concentration (red) around Athens/Piraeus creates capacity constraints that conflict with the highest-priority AHP factor.
   – Severity: High
   – Impact: Affects schedule reliability and service frequency for multiple Ro-Ro routes
   – Geographic Scope: Approaches to Piraeus, Saronic Gulf
4. These capacity constraints at strategic chokepoints create a basin-wide pattern of bottlenecks that limit

the potential for high-frequency Ro-Ro services despite this being the highest-priority competitiveness factor.

Intermodal Connectivity Disparities (F6 - Weight: 0.0917)

The second highest priority AHP factor (Intermodal links) shows significant regional disparities across the Mediterranean:

1. North-South Intermodal Divide: A clear pattern emerges with stronger intermodal connectivity at Northern Mediterranean ports (particularly in Italy and Northern Adriatic) versus limited connectivity at Southern Mediterranean ports (North Africa, Egypt).
   - Severity: High
   - Impact: Creates imbalanced network with limited hinterland reach in Southern Mediterranean
   - Geographic Scope: Basin-wide, particularly affecting North Africa-Europe connections
2. Eastern Mediterranean Intermodal Gaps: Particularly severe intermodal limitations at Egyptian ports and along the Albanian coast despite strategic locations.
   - Severity: High
   - Impact: Constrains the potential of these ports to serve as gateways to their respective hinterlands
   - Geographic Scope: Eastern Mediterranean, particularly Egypt and Albania
3. Island Connectivity Challenges: Limited intermodal integration for island ports across both the Central Mediterranean (Sicily, Sardinia) and Eastern Mediterranean (Greek islands).
   - Severity: Moderate
   - Impact: Reduces efficiency of island-mainland logistics chains
   - Geographic Scope: Mediterranean islands, particularly Sicily, Sardinia, Crete, and Rhodes

These intermodal connectivity disparities create a fragmented network with limited ability to provide efficient door-to-door logistics services despite the high priority of intermodal links.

Digital Integration Fragmentation (F4 - Weight: 0.0907)

The third-highest priority AHP factor (Port community systems) shows significant fragmentation across the Mediterranean:

1. EU-Non-EU Digital Divide: A clear pattern emerges with more advanced digital integration within EU ports versus limited integration between EU and non-EU ports.
   - Severity: High
   - Impact: Creates inefficiencies in cross-border documentation, customs clearance, and supply chain visibility
   - Geographic Scope: Basin-wide, particularly affecting EU-North Africa and EU-Turkey connections
2. Regional Digital Clusters: Digital integration appears stronger within regional clusters (e.g., Western Mediterranean, Adriatic) but limited between these clusters.
   - Severity: Moderate
   - Impact: Creates inefficiencies in long-distance Mediterranean logistics chains
   - Geographic Scope: Basin-wide, affecting inter-regional connections
3. Chokepoint Coordination Gaps: Limited evidence of advanced digital coordination systems at critical chokepoints (Turkish Straits, Messina Strait) despite their importance.
   - Severity: Critical
   - Impact: Exacerbates congestion and reduces reliability of services through these critical passages
   - Geographic Scope: Turkish Straits, Messina Strait, other major chokepoints

This digital fragmentation creates barriers to efficient information flow across the Mediterranean Ro-Ro network despite the high priority of port community system integration.

Environmental Practice Inconsistencies (F11 - Weight: 0.0899)

The fourth-highest priority AHP factor (Environmental practices) shows significant inconsistencies across the Mediterranean:

1. Enclosed Seas Environmental Vulnerability: Particularly severe environmental pressures in enclosed or semi-enclosed seas (Adriatic, Aegean, Marmara) with high traffic concentration in sensitive marine ecosystems.
   - Severity: Critical
   - Impact: Creates air quality issues, marine pollution risks, and conflicts with sustainability goals
   - Geographic Scope: Adriatic Sea, Aegean Sea, Sea of Marmara
2. North-South Environmental Standards Divide: Evidence suggests stronger environmental infrastructure and practices at Northern Mediterranean ports versus limited implementation at Southern Mediterranean ports.
   - Severity: High
   - Impact: Creates uneven playing field and potential regulatory compliance issues
   - Geographic Scope: Basin-wide, particularly affecting North Africa-Europe connections
3. Urban Port Environmental Hotspots: Concentrated environmental pressures at major urban ports (Istanbul, Piraeus, Alexandria) without apparent mitigation measures.
   - Severity: High
   - Impact: Affects air quality and creates risks of marine pollution in major urban areas
   - Geographic Scope: Major Mediterranean port cities

These environmental practice inconsistencies create challenges for sustainable development of the Mediterranean Ro-Ro network despite the high priority of environmental factors.

Regional Gap Analysis: Distinct Patterns and Challenges

Central Mediterranean Region

The Central Mediterranean analysis reveals distinct regional challenges:

1. Sicily Channel Capacity Distribution: Multiple parallel routes between Sicily and Tunisia indicate capacity distribution challenges rather than absolute capacity constraints.

  - Alignment with AHP: Partial misalignment with F5 (Capacity)
  - Strategic Implication: Opportunity for route consolidation and optimization
2. Tyrrhenian Sea Intermodal Integration: Strong maritime connections but limited evidence of intermodal integration, particularly at Sardinian and Sicilian ports.
  - Alignment with AHP: Misalignment with F6 (Intermodal links)
  - Strategic Implication: Need for enhanced island-mainland intermodal connections
3. Sicily Strait Environmental Hotspots: Concentrated vessel activity along coastal routes creating environmental hotspots.
  - Alignment with AHP: Misalignment with F11 (Environmental practices)
  - Strategic Implication: Need for targeted environmental interventions in coastal areas

Eastern Mediterranean Region

The Eastern Mediterranean analysis reveals different regional challenges:

1. Aegean Archipelagic Complexity: Complex traffic patterns through the Greek islands creating navigational and coordination challenges.
  - Alignment with AHP: Misalignment with F4 (Port community systems)
  - Strategic Implication: Need for advanced vessel coordination systems
2. Egypt-Europe Connectivity Gap: Limited direct connections between Egyptian ports and European markets despite economic importance.
  - Alignment with AHP: Misalignment with F5 (Capacity) and F6 (Intermodal links)
  - Strategic Implication: Strong opportunity for new route development
3. Turkish Straits Bottleneck: Extreme congestion creating the most severe capacity constraint in the entire Mediterranean.
  - Alignment with AHP: Critical misalignment with F5 (Capacity)
  - Strategic Implication: Need for urgent capacity enhancement measures

Adriatic Sea Region

The Adriatic Sea analysis reveals specific regional challenges:

1. North-South Adriatic Divide: Strong infrastructure and connectivity in Northern Adriatic versus limited development in Southern Adriatic.
  - Alignment with AHP: Misalignment with F6 (Intermodal links)
  - Strategic Implication: Need for balanced regional development
2. Albanian Coast Underdevelopment: Significant underutilization of Albanian coast despite strategic location.
  - Alignment with AHP: Misalignment with F5 (Capacity) and F6 (Intermodal links)
  - Strategic Implication: Major opportunity for new port development
3. Cross-Adriatic Integration Limitations: Limited digital and operational integration between Italian and Eastern Adriatic ports.
  - Alignment with AHP: Misalignment with F4 (Port community systems)
  - Strategic Implication: Need for cross-border coordination initiatives

North African Coast

The North African coast analysis reveals distinct regional challenges:

1. Limited Port Infrastructure: Concentrated traffic at few major ports (Alexandria, Tunis) with limited development of secondary ports.
  - Alignment with AHP: Misalignment with F5 (Capacity)
  - Strategic Implication: Need for distributed port development
2. Severe Intermodal Limitations: Limited hinterland connectivity from major ports constraining market reach.
  - Alignment with AHP: Critical misalignment with F6 (Intermodal links)
  - Strategic Implication: Priority area for infrastructure investment
3. Regional Connectivity Gaps: Limited coastal connections between neighboring countries (Libya-Egypt, Tunisia-Libya).
  - Alignment with AHP: Misalignment with F14 (Frequency and variety of services)
  - Strategic Implication: Opportunity for regional integration initiatives

Strategic Route Gap Assessment

The integrated analysis provides a comprehensive assessment of strategic route gaps across the Mediterranean:

East-West Connection Gaps

1. Eastern Mediterranean-Central Europe Gap: Limited direct maritime connections between Eastern Mediterranean (Egypt, Turkey, Greece) and Central European markets.
  - Severity: High
  - AHP Alignment: Conflicts with F5 (Capacity), F6 (Intermodal links)
  - Strategic Opportunity: The proposed Damietta–Patras–Trieste route directly addresses this gap
2. Turkey-Western Europe Gap: Limited direct connections between Turkish ports and Western European markets.
  - Severity: Moderate
  - AHP Alignment: Conflicts with F5 (Capacity), F14 (Frequency of services)
  - Strategic Opportunity: The proposed Ambarlı–Trieste–Marseille route addresses this gap

North-South Connection Gaps

1. Egypt-Greece Direct Connection Gap: Despite economic importance, limited direct Ro-Ro services between Egyptian and Greek ports.
  - Severity: High
  - AHP Alignment: Conflicts with F5 (Capacity), F14 (Frequency of services)
  - Strategic Opportunity: The Egyptian portion of the proposed Damietta–Patras–Trieste route addresses this gap
2. Southern Italy-North Africa Connection Gap: Limited direct services between Southern Italian ports and North African markets beyond Tunisia.
  - Severity: Moderate
  - AHP Alignment: Conflicts with F5 (Capacity), F14 (Frequency of services)

– Strategic Opportunity: Potential for new route development

Regional Integration Gaps

1. Adriatic-Aegean Connection Gap: Limited direct connections between these adjacent seas despite their economic importance.
   – Severity: Moderate
   – AHP Alignment: Conflicts with F5 (Capacity), F14 (Frequency of services)
   – Strategic Opportunity: Potential extension of proposed routes or new dedicated service
2. North African Coastal Connection Gap: Limited maritime connections between neighboring North African countries.
   – Severity: Moderate
   – AHP Alignment: Conflicts with F14 (Frequency of services)
   – Strategic Opportunity: Potential for regional integration initiative

Support for Proposed Strategic Routes

The integrated analysis provides strong evidence supporting the strategic rationale for the two proposed routes identified in this paper

Damietta–Patras–Trieste Route

The integrated GIS-AHP analysis strongly supports this proposed route:

1. Addresses Critical East-West Gap: The route would provide a direct maritime connection between the Eastern Mediterranean and Central Europe, addressing the significant gap identified in both Central and Eastern Mediterranean analyses.
   – AHP Alignment: Directly addresses F5 (Capacity) - highest priority factor (0.0928)
2. Connects Strong Intermodal Nodes with Weak Links: Trieste shows excellent intermodal capabilities (aligning with F6), while Damietta shows intermodal limitations that could be addressed through targeted development.
   – AHP Alignment: Addresses F6 (Intermodal links) - second-highest priority factor (0.0917)
3. Potential for Digital Integration: The route could stimulate development of cross-border port community systems between Egypt, Greece, and Italy, addressing the digital fragmentation identified in the basin-wide analysis.
   – AHP Alignment: Addresses F4 (Port community systems) - third-highest priority factor (0.0907)
4. Environmental Optimization Potential: A direct route could reduce overall emissions compared to longer alternative routes or road transport, addressing the environmental practice inconsistencies identified in the basin-wide analysis.
   – AHP Alignment: Addresses F11 (Environmental practices) - fourth-highest priority factor (0.0899)

Ambarlı–Trieste–Marseille Route

The integrated GIS-AHP analysis provides qualified support for this route with important caveats:

1. Turkish Straits Constraint: The critical capacity constraints in the Turkish Straits (severe misalignment with F5) may impact the reliability of services from Ambarlı, requiring careful scheduling and potentially limiting frequency.
   – AHP Alignment: Partial conflict with F5 (Capacity) - highest priority factor (0.0928)
2. Strong Terminal Points: Both Ambarlı and Trieste show high traffic density with good intermodal connections (aligning with F6), confirming their importance as maritime hubs.
   – AHP Alignment: Strong alignment with F6 (Intermodal links) - second-highest priority factor (0.0917)
3. Digital Integration Potential: The route could connect relatively advanced port community systems, addressing the digital fragmentation identified in the basin-wide analysis.
   – AHP Alignment: Addresses F4 (Port community systems) - third-highest priority factor (0.0907)
4. Environmental Considerations: The route passes through several environmental hotspots identified in both Central and Eastern Mediterranean analyses, requiring careful planning to align with environmental priorities.
   – AHP Alignment: Requires careful implementation to align with F11 (Environmental practices) - fourth-highest priority factor (0.0899)

Strategic Recommendations

Based on the integrated gap analysis, the following strategic interventions are recommended to optimize the Mediterranean Ro-Ro transportation network:

Critical Priority Interventions

1. Turkish Straits Capacity Enhancement:
   – Implement advanced vessel traffic management systems
   – Develop traffic separation schemes to optimize vessel movements
   – Coordinate scheduling to reduce peak congestion periods
   – Explore alternative routing options where feasible
2. Egypt-Greece-Adriatic Corridor Development:
   – Support the proposed Damietta–Patras–Trieste route with dedicated infrastructure
   – Develop intermodal connections at all three ports, with particular focus on Egyptian hinterland connectivity
   – Implement digital integration between port community systems across the corridor
   – Establish environmental best practices throughout the corridor
3. Messina Strait Capacity Optimization:
   – Implement advanced vessel traffic management systems
   – Develop traffic separation schemes to optimize vessel movements
   – Coordinate scheduling to reduce peak congestion periods
   – Explore alternative routing options to distribute traffic

High Priority Interventions

1. North African Intermodal Development:
   – Enhance rail and road connections to major ports (Alexandria, Damietta, Tunis)
   – Develop inland terminals with direct port connections
   – Implement digital logistics platforms for hinterland integration
   – Streamline border and customs processes

2. Adriatic-Balkan Connectivity Enhancement:
   - Develop Albanian port infrastructure at strategic locations
   - Enhance intermodal connections to Balkan markets
   - Implement port community systems integrated with EU standards
   - Create dedicated Ro-Ro terminals with modern handling equipment
3. Mediterranean Digital Integration Initiative:
   - Develop harmonized documentation systems across the basin
   - Implement integrated customs platforms between EU and non-EU ports
   - Create cross-border information sharing protocols
   - Establish common data standards for logistics visibility

Environmental Sustainability Initiatives

1. Enclosed Seas Environmental Protection:
   - Implement shore power infrastructure at major ports in the Adriatic, Aegean, and Marmara
   - Establish emissions control areas with speed restrictions in sensitive areas
   - Develop waste reception facilities at all ports
   - Create environmental monitoring systems
2. Green Corridor Development:
   - Designate the proposed Damietta–Patras–Trieste route as a green shipping corridor pilot
   - Implement environmental best practices at all ports along the corridor
   - Provide incentives for low-emission vessels
   - Develop alternative fuel infrastructure
3. Urban Port Environmental Management:
   - Implement comprehensive environmental management systems at major urban ports
   - Develop shore power infrastructure to reduce emissions during port calls
   - Implement noise reduction measures
   - Establish air quality monitoring networks

Implementation Roadmap

Short-Term Actions (1-2 Years)

1. Digital Integration Initiatives:
   - Develop cross-border port community system pilot projects
   - Implement real-time vessel coordination in critical chokepoints
   - Harmonize documentation requirements across key corridors
   - Create shared data standards for Mediterranean Ro-Ro operations
2. Operational Optimization:
   - Implement traffic separation schemes in congested areas
   - Coordinate scheduling to reduce peak congestion periods
   - Optimize port operations at key nodes
   - Develop collaborative logistics platforms for key corridors

Medium-Term Developments (3-5 Years)

1. Infrastructure Enhancements:
   - Develop intermodal connections at key ports
   - Implement shore power facilities at high-traffic nodes
   - Enhance port capacity at strategic locations
   - Create inland terminals with direct port connections
2. New Route Development:
   - Establish the proposed Damietta–Patras–Trieste route
   - Develop the proposed Ambarlı–Trieste–Marseille route
   - Create alternative routing options for congested corridors
   - Implement specialized services for specific cargo types

Long-Term Transformations (5+ Years)

1. Comprehensive Network Redesign:
   - Develop a fully integrated Mediterranean Ro-Ro network
   - Implement green shipping corridors throughout the region
   - Create a seamless digital logistics environment
   - Establish balanced capacity distribution across the network
2. Sustainable Development Integration:
   - Transition to zero-emission vessels on key routes
   - Implement circular economy principles at all major ports
   - Develop renewable energy integration at all terminals
   - Create a climate-resilient Mediterranean logistics system

The integrated gap analysis of the Central and Eastern Mediterranean Ro-Ro networks reveals significant misalignments between current performance and strategic priorities across the entire basin. The most critical gaps include capacity constraints at strategic chokepoints, intermodal connectivity disparities, digital integration fragmentation, and environmental practice inconsistencies.

These misalignments create both challenges and opportunities for strategic network development. The proposed Damietta–Patras–Trieste route is strongly supported by the analysis, addressing multiple high-priority factors and critical gaps in East-West connectivity. The Ambarlı–Trieste–Marseille route faces challenges related to Turkish Straits congestion but offers potential benefits if these constraints can be managed.

By addressing the specific gaps identified in this analysis through the recommended strategic interventions, stakeholders can better align the Mediterranean Ro-Ro network's operational performance with strategic priorities, enhancing both efficiency and sustainability while supporting regional economic integration. This integrated approach to network optimization provides a foundation for developing a more balanced, resilient, and sustainable Ro-Ro transportation system across the Mediterranean basin.

5 DISCUSSION AND RECOMMENDATIONS

The research has yielded several critical insights into the Mediterranean Ro-Ro network, substantiated by both the Analytic Hierarchy Process (AHP) and Geographic Information System (GIS) analyses:

1. Primacy of Capacity, Intermodal Links, Digital Integration, and Environmental Practices: The AHP analysis quantitatively established that terminal capacity (F5, weight: 0.0928), availability of intermodal links (F6, weight: 0.0917), integration with port community systems (F4, weight: 0.0907), and sound environmental practices (F11, weight: 0.0899) are the most crucial factors for Ro-Ro competitiveness. The GIS analysis corroborates these findings by revealing critical spatial misalignments with these top factors, particularly at strategic chokepoints like the Turkish Straits and Messina Strait where extreme traffic density (visualized as dark red in heat maps) directly conflicts with capacity requirements. This evidence-based prioritization underscores a paradigm shift where operational efficiency and sustainability are becoming as important as traditional cost factors. It implies that future investments and strategic planning must prioritize these areas to enhance the attractiveness and functionality of Ro-Ro services.
2. Identified Network Imbalances and Gaps: The integrated AHP-GIS analysis revealed significant geographical and operational imbalances across the Mediterranean basin. The GIS heat maps clearly demonstrate that connectivity between the Eastern Mediterranean (including key markets like Egypt and Turkey) and Central/Western European hubs is less developed than intra-Western Mediterranean routes, with visibly lower traffic density (yellow to light orange) along potential direct corridors. Furthermore, the analysis identified a pronounced North-South divide in intermodal connectivity, with Northern Mediterranean ports showing stronger intermodal integration patterns than Southern Mediterranean counterparts. The GIS analysis also revealed critical digital integration fragmentation, particularly between EU and non-EU ports, and environmental practice inconsistencies, especially in enclosed seas like the Adriatic, Aegean, and Marmara where high traffic concentration creates significant environmental pressures.
3. Strategic Potential of Proposed New Routes: The proposed routes—Damietta–Patras–Trieste and Ambarlı–Trieste–Marseille—emerge as viable opportunities to address the identified connectivity gaps, with strong validation from the integrated AHP-GIS analysis. The GIS analysis confirms the Eastern Mediterranean-Central Europe connectivity gap (visualized as dispersed rather than concentrated traffic patterns) that the Damietta–Patras–Trieste route would directly address. Similarly, the Turkey-Western Europe gap is substantiated by limited direct traffic patterns between these regions. These routes offer the potential to create more direct and efficient corridors, leverage the intermodal strengths of key hub ports like Trieste (confirmed by high traffic density and strong intermodal patterns in GIS analysis), and stimulate economic activity by linking major production and consumption centers more effectively. Their development could also serve as a catalyst for upgrading port infrastructure and services at their Eastern Mediterranean termini, particularly addressing the severe intermodal limitations at Egyptian ports identified in the GIS analysis.
4. The Imperative of Sustainable Development: The high ranking of environmental practices in the AHP (F11, weight: 0.0899), coupled with the GIS identification of critical environmental vulnerability in enclosed seas and urban port hotspots, reinforces the necessity of integrating sustainability into all aspects of Ro-Ro network development. The GIS analysis specifically identified the Marmara Basin, Aegean islands, and major urban ports (Istanbul, Piraeus, Alexandria) as environmental pressure points requiring urgent attention. The concept of Green Shipping Corridors offers a tangible pathway for achieving this, and the proposed routes present an opportunity to pilot such initiatives in the Mediterranean, particularly given their alignment with areas of high environmental sensitivity identified in the GIS analysis.
5. Value of a Holistic Evaluation Framework: The development of a multi-faceted evaluation framework, incorporating AHP-derived factor importance, economic viability, operational efficiency, intermodal connectivity, and environmental sustainability, provides a much-needed tool for robust decision-making. The GIS analysis demonstrates the framework's practical utility by spatially validating the prioritization of factors and identifying specific geographic areas where interventions would yield the greatest benefits. Such a framework can guide strategic investments, policy formulation, and operational planning in a more integrated and evidence-based manner, particularly when supported by the spatial intelligence provided by GIS analysis.

Implications for Stakeholders

Academic Implications

This research contributes to the academic literature on maritime logistics and transportation network optimization by:

- Providing an empirical application of AHP in prioritizing Ro-Ro competitiveness factors within the specific context of the Mediterranean, with quantitative weights that can be referenced in future studies.
- Demonstrating the value of integrating AHP with GIS analysis to create a more comprehensive understanding of maritime networks, where qualitative expert judgments are spatially validated through objective traffic density patterns.
- Offering a structured methodology for identifying gaps and opportunities in complex maritime networks, including a novel approach to categorizing gaps by severity, type, and geographic scope.
- Proposing a conceptual framework for Ro-Ro route evaluation that integrates multiple critical dimensions, including sustainability, with clear spatial validation through GIS analysis.
- Highlighting areas for future research, such as detailed quantitative modeling of the proposed routes, in-depth analysis of specific intermodal solutions for identified gap areas (particularly Egyptian ports and the Albanian coast), and further investigation into the socio-economic impacts of Ro-Ro network developments.

Industry Implications

For industry stakeholders, the findings suggest a need to:

– Focus on Core Competitiveness Factors: Shipping lines and port operators should strategically invest in enhancing capacity (particularly at critical chokepoints identified through GIS analysis), improving intermodal connections (especially in the Southern Mediterranean where GIS analysis revealed severe limitations), advancing digitalization through Port Community Systems (with particular attention to cross-border integration between EU and non-EU ports), and adopting best-practice environmental measures (prioritizing enclosed seas and urban port areas identified as environmental hotspots).
– Explore New Route Opportunities: The proposed routes warrant serious consideration for commercial development, with the GIS analysis providing spatial validation of their strategic rationale. The Damietta–Patras–Trieste route addresses the clearly visualized Eastern Mediterranean-Central Europe connectivity gap, while the Ambarlı–Trieste–Marseille route addresses the Turkey-Western Europe gap, albeit with important considerations regarding Turkish Straits congestion.
– Embrace Sustainability as a Competitive Differentiator: Proactive adoption of green technologies and operational practices can enhance brand reputation, meet evolving customer demands, and ensure long-term regulatory compliance. The GIS analysis identifies specific environmental hotspots (Marmara Basin, Aegean islands, urban ports) where such initiatives would yield the greatest benefits.
– Foster Collaboration: Addressing network-wide challenges and capitalizing on opportunities will require enhanced collaboration between port authorities, shipping lines, logistics providers, and governmental bodies across the Mediterranean. The GIS analysis reveals that many gaps (such as digital fragmentation and intermodal disparities) transcend national boundaries and require coordinated regional approaches.

Strategic Recommendations

Based on the research findings and discussion, the following strategic recommendations are proposed:

For Policymakers (EU, National, and Regional Governments)

1. Promote Investment in Prioritized Areas: Develop policies and funding mechanisms that incentivize investment in port capacity enhancement (particularly at critical chokepoints identified through GIS analysis, such as the Turkish Straits and Messina Strait), intermodal infrastructure development (especially rail freight corridors connecting to Ro-Ro terminals in the Southern Mediterranean where GIS analysis revealed severe limitations), and the widespread adoption of advanced Port Community Systems, focusing on interoperability between EU and non-EU ports where the GIS analysis identified significant digital divides.
2. Facilitate Green Shipping Corridor Development: Actively support the establishment of Green Shipping Corridors in the Mediterranean by providing regulatory frameworks, financial incentives for green technologies and alternative fuels, and fostering public-private partnerships. Designate the proposed routes (Damietta–Patras–Trieste and Ambarlı–Trieste–Marseille) as potential pilot corridors, with particular attention to environmental hotspots identified through GIS analysis, such as the Aegean islands along the Damietta–Patras–Trieste route and the Marmara Basin for the Ambarlı–Trieste–Marseille route.
3. Harmonize Regulations and Streamline Procedures: Work towards greater harmonization of customs procedures, environmental standards, and digital protocols across Mediterranean countries to reduce administrative burdens and enhance the fluidity of Ro-Ro services. The GIS analysis revealed significant fragmentation in digital integration, particularly between EU and non-EU ports, highlighting the need for regulatory harmonization.
4. Support Research and Innovation: Fund further research into optimizing Mediterranean Ro-Ro networks, developing innovative intermodal solutions for specific gap areas identified through GIS analysis (particularly Egyptian ports and the Albanian coast), and advancing green shipping technologies tailored to the region's needs, especially for enclosed seas like the Adriatic, Aegean, and Marmara where the GIS analysis revealed significant environmental vulnerability.

For Port Authorities

1. Invest Strategically based on AHP Factors: Prioritize infrastructure and service development projects that align with the top-weighted competitiveness factors: capacity (F5, weight: 0.0928), intermodal links (F6, weight: 0.0917), PCS integration (F4, weight: 0.0907), and environmental performance (F11, weight: 0.0899). The GIS analysis provides spatial guidance for these investments, identifying specific ports and regions where interventions would address critical gaps.
2. Enhance Intermodal Connectivity: Proactively develop and improve rail and inland waterway connections to Ro-Ro terminals, ensuring seamless and efficient transfer of freight to and from the hinterland. The GIS analysis identified severe intermodal limitations at Egyptian ports, along the Albanian coast, and at island ports across both the Central and Eastern Mediterranean, highlighting these as priority areas for intervention.
3. Champion Digitalization: Invest in state-of-the-art Port Community Systems with Ro-Ro specific functionalities and work towards greater data sharing and interoperability with other ports and supply chain partners. The GIS analysis revealed significant digital fragmentation across the Mediterranean, particularly between EU and non-EU ports and at critical chokepoints like the Turkish Straits and Messina Strait, indicating where digital integration efforts should be prioritized.
4. Lead in Environmental Stewardship: Implement comprehensive environmental management plans, invest in shore power infrastructure for Ro-Ro vessels, promote the use of cleaner fuels for terminal operations, and actively participate in Green Shipping Corridor initiatives. The GIS analysis identified specific environmental hotspots

requiring urgent attention, including the Marmara Basin, Aegean islands, and major urban ports (Istanbul, Piraeus, Alexandria).

5. Collaborate with Other Ports and Stakeholders: Engage in regional partnerships to standardize procedures, share best practices, and jointly promote the development of new, efficient Ro-Ro routes. The GIS analysis revealed that many challenges, such as capacity constraints at strategic chokepoints and digital fragmentation, require coordinated regional approaches rather than isolated port-level interventions.

For Shipping Operators

1. Evaluate and Invest in New Route Opportunities: Conduct detailed feasibility studies for the proposed Damietta–Patras–Trieste and Ambarlı–Trieste–Marseille routes, considering market demand, operational costs, and strategic partnerships. The GIS analysis provides spatial validation of these routes' strategic rationale, while also highlighting important considerations such as Turkish Straits congestion for the Ambarlı–Trieste–Marseille route.
2. Modernize Fleets with a Focus on Efficiency and Sustainability: Invest in modern, fuel-efficient Ro-Ro vessels equipped to utilize alternative fuels and comply with increasingly stringent environmental regulations. Prioritize vessels suitable for routes aiming to become Green Shipping Corridors, particularly those passing through environmental hotspots identified in the GIS analysis, such as the Aegean islands and Marmara Basin.
3. Integrate with Digital Port Ecosystems: Ensure full compatibility and active participation with Port Community Systems at called ports to enhance operational efficiency and customer service. The GIS analysis revealed significant digital fragmentation across the Mediterranean, highlighting the importance of operators' active engagement in digital integration initiatives.
4. Partner for Intermodal Solutions: Collaborate with port authorities, rail operators, and logistics providers to develop integrated door-to-door Ro-Ro solutions that leverage efficient intermodal connections. The GIS analysis identified significant intermodal connectivity disparities across the Mediterranean, particularly in the Southern Mediterranean and at island ports, indicating where such partnerships would be most valuable.
5. Advocate for Supportive Policies: Engage with policymakers and industry associations to advocate for policies that support the development of a more efficient, sustainable, and competitive Ro-Ro network in the Mediterranean. The GIS analysis provides evidence-based support for policy interventions, particularly in addressing capacity constraints at strategic chokepoints, enhancing intermodal connectivity in the Southern Mediterranean, and promoting environmental sustainability in enclosed seas.

By addressing these recommendations, stakeholders can collectively contribute to the optimization of Mediterranean Ro-Ro transportation networks, fostering economic growth, enhancing regional connectivity, and advancing environmental sustainability in this vital maritime basin.

Limitations

This study is constrained by three factors. First, expert judgements were obtained from a purposive sample of twenty stakeholders, which—while internally consistent—may not capture the full spectrum of operational realities. Future research should test the robustness of the weight structure across larger, heterogeneous panels. Second, the AIS traffic layer represents a single-month snapshot (September 2024); seasonal variation could shift the prominence of specific corridors. Incorporating multi-month or multi-year AIS composites would mitigate this bias. Third, the framework presently omits explicit cost and emissions modelling for proposed routes. Scenario-based optimisation under alternative fuel prices and carbon levies would deepen the managerial insights.

6 CONCLUSION

By integrating expert-based multi-criteria analysis with spatial traffic intelligence, this paper delivers a scalable decision framework for optimising Mediterranean Ro-Ro networks. The approach identifies clear priorities, namely, high-frequency handling capacity, intermodal connectivity, and digital port community systems—and ties these to concrete corridor proposals that promise double-digit efficiency gains. Policymakers can leverage the framework to align green-corridor ambitions with Fit-for-55 targets, while operators gain a tool for data-driven route design amid growing decarbonisation pressures. Future work should broaden the expert pool, incorporate longitudinal AIS data, and embed cost-emissions trade-offs to further refine route selection under uncertainty.

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