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Envisioning AI for international cooperation in maritime transport: conceptual insights from short sea shipping and maritime spatial planning ☆

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ABSTRACT

Artificial Intelligence (AI) can significantly enhance transportation governance, particularly by enabling more effective international cooperation in data-driven decision-making. In maritime transport, AI applications can support complex planning and policy processes, such as maritime spatial planning (MSP), which governs the use of maritime space across overlapping sectors and jurisdictions. Short sea shipping (SSS), a vital mode of regional and intra-regional transport, depends heavily on coordinated planning efforts due to its interactions with other marine uses, its socio-economic role, and the need to maintain connectivity for insular economies.

This study uses a national level case study of Greek SSS to identify structural, data-related, and governance limitations that impede evidence-based policy design. Key performance indicators (KPIs) and composite indices (CIs) are developed to assess connectivity, accessibility, and operational efficiency across the island and between the islands and the mainland. These empirical findings reveal fragmented data, heterogenous service patterns, and gaps in current governance frameworks, highlighting challenges that extend to regional and international coordination.

Building on these insights, the paper proposes a conceptual AI framework to address the identified limitations. Machine learning can forecast SSS performance trands, while natural language processing can harmonize policy documents across jurisdictions. By linking empirical limitations with this forward-looking conceptual approach, the study demonstrates how AI can transform fragmented maritime data into interoperable, collaborative governance mechanisms that enhance MSP implementation and cross-border cooperation.

1. Introduction

International maritime governance and Maritime Spatial Planning (MSP) are increasingly required to address complex, multi-sectoral, and multi-scalar challenges, including spatial competitions, sustainability objectives, and territorial cohesion. While MSP has been institutionalized as a key governance instrument, its practical effectiveness is often constrained by persistent gaps in measurable indicators, limited data harmonization, and the lack of systematic and comparable monitoring frameworks across regions and countries.

Within this governance context, short sea shipping (SSS) plays a critical role in the transportation of passengers and goods and constitutes a fundamental mechanism for achieving territorial cohesion, particularly in island and coastal regions. In geographically fragmented countries such as Greece, SSS mitigates socio-economic disparities by ensuring connectivity and accessibility to socially and economically significant destinations and resources, thereby addressing structural constraints related to insularity, remoteness, and small population size (Bradley et al., 2017; Chlomoudis et al., 2011; Official Journal of the EU, 2007). From a social perspective, reliable SSS services enhance the quality of life for island residents by facilitating access to essential services, employment, and education (Mitropoulos, 2011). Economically, SSS supports market openness and competitiveness and has been shown to strongly correlate with regional economic growth compared to other modes of transport (Park et al., 2019).

Beyond transport function, SSS is embedded within broader maritime governance systems and interacts with multiple economic sectors as well as social and environmental dimensions. Its planning and regulation therefore require robust governance frameworks, with MSP playing a central role in balancing competing uses while promoting territorial cohesion at regional, national, and international scales (Mitropoulos, 2011). However, translating territorial cohesion

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objectives into operational MSP outcomes remains challenging, particularly in multi-level and cross-border contexts, where governance arrangements, data availability, and analytical practices differ substantially (Zaucha, 2019).

A persistent limitation in both MSP and SSS-related policies is the absence of concrete qualitative and quantitative standards for assessing territorial cohesion. This gap is particularly evident in the maritime domain, where cohesion considerations are often underrepresented, partly due to assumptions about limited human presence at sea (Zaucha, 2019; CPMR, n.d.), despite the growing demand for marine space across multiple sectors (Sangiuliano, 2018). As emphasized by Zaucha and Böhme (2019), while territorial cohesion is measurable, its assessment should rely on clearly defined, transparent, and policy-relevant indicators that are applicable across different geographic scales. This underscores the need for structured and reproducible indicator frameworks capable of capturing key dimensions of connectivity and accessibility in maritime transport networks.

Responding to this gap, this paper focuses on passenger transportation within the Greek domestic SSS network and develops two composite indicators (CIs) that quantify island connectivity and accessibility through the aggregation of carefully selected key performance indicators (KPIs). The indicators are calculated for the baseline year 2018, providing a stable pre-pandemic reference for benchmarking island performance, identifying spatial disparities, and supporting evidence-based policymaking. Although the empirical application is national, the proposed methodological framework is explicitly designed to be transferable to other SSS contexts, including cross-border SSS systems and different transport segments, thereby supporting broader MSP and maritime governance objectives.

At the same time, the increasing volume, heterogeneity, and temporal dynamics of maritime transport data pose growing challenges for traditional analytical approaches, particularly in international governance settings where data integration, comparability, and continuous monitoring are critical. These challenges motivate the exploration of advanced data-driven tools, including Artificial Intelligence (AI), not as replacement of indicator-based analysis but as an enabling technology. AI can support the scaling, automation, and regular updating of CI frameworks, facilitate data harmonization across jurisdictions, and enhance adaptive monitoring within MSP processes. While AI methods are not applied empirically in this study, their conceptual integration is discussed to illustrate how the proposed framework could be operationalized more efficiently in future multi-regional and cross-border applications.

The remainder of the paper is structured as follows. Section 2 reviews the relevant scientific background. Section 3 outlines the methodological approach and the case study context. Section 4 presents the results, followed by their discussion in Section 5. Section 6 concludes with policy implications and recommendations.

2. Scientific background

2.1. The concepts of territorial cohesion and insularity for island connectivity

Territorial cohesion in coastal and island contexts is closely linked to insularity, a concept that captures the structural disadvantages arising from geographic dispersion, remoteness, and physical separation from major economic and administrative centers (van den Bossche et al., 2021; Garau et al., 2020; Mitropoulou & Spilanis, 2020; Theodora, 2020; Cocco et al., 2019; Gløersen et al., 2019; Licio & Pinna, 2013; Briguglio, 1995). These characteristics manifest in fragmented transport networks, longer distances from the mainland and between islands, and reduced access to essential socio-economic functions such as health, employment, education, markets, resources, and public services (van den Bossche et al., 2021; Garau et al., 2020; Mitropoulou & Spilanis, 2020; Gløersen et al., 2019; Licio & Pinna, 2013; Briguglio, 1995). Within this context, territorial cohesion is not merely a spatial policy goal but a functional condition that depends critically on the performance of transport connectivity.

Islands face higher transport costs and lower service efficiency, reflecting both physical constraints and structural market limitations (van den Bossche et al., 2021; Gløersen et al., 2019; Armstrong & Read, 2004). Waterborne and air transport services are essential (van den Bossche et al., 2021; Gløersen et al., 2019; Deidda, 2016; Licio & Pinna, 2013; Briguglio, 1995), yet they are constrained by small-scale operations, limited demand, and the absence of economies of scale (van den Bossche et al., 2021; Deidda, 2016; Sufrauj, 2011; Briguglio, 1995). These conditions reduce service frequency and capacity, increase travel times, and often result in indirect routes, reinforcing accessibility deficits and affecting regional competitiveness, social inclusion, and economic resilience (Tsekeris, 2022; van den Bossche et al., 2021; Deidda, 2016; Spilanis et al., 2013a; Armstrong & Read, 2004; Briguglio, 1995).

However, territorial cohesion extends beyond transport cost considerations. Travel behavior and perceived accessibility are influenced by multiple interrelated factors, including service frequency, reliability, travel time, and modal availability (Levy & Panou, 2010; Cross & Nutley, 1999). Moreover, additional vulnerabilities, like small population size, demographic decline, climate exposure, and external shocks, further amplify cohesion challenges in peripheral and remote islands. These dynamics underscore that connectivity and accessibility are multidimensional constructs that can be systematically measured rather than abstract policy ideals.

Recognizing these dimensions is crucial for designing structured indicator frameworks capable of translating complex transport and spatial interactions into comparable metrics. Such frameworks provide an operational basis for monitoring, evidence-based policymaking, and MSP. By identifying which aspects of SSS most effectively affect territorial cohesion, measurable indicators can inform both national and cross-border governance processes. This foundation also highlights the potential role of advanced analytical tools, including AI, in supporting data harmonization, monitoring, and evaluation, issues explored in Sections 2.3 and 2.4.

Overall, understanding insularity and connectivity challenges provides a conceptual link between territorial cohesion, measurable KPIs, and the broader opportunities for harmonized, AI-supported monitoring and evaluation, forming the basis for the empirical and methodological contributions of this study.

2.2. Measuring territorial cohesion dimensions

Territorial cohesion in island and coastal regions is fundamentally mediated through connectivity and accessibility, which can be operationalized and monitored using KPIs and CIs. Over the past decades, several indices have been developed to quantify these dimensions, reflecting different conceptualizations of connectivity and accessibility.

Relevant approaches for measuring accessibility like Territorial Accessibility Index (TAI) (Teclean and Drăgan, 2020) and the Multimodal Accessibility Index (MAI) (ESPON, 2006), focused on infrastructure density, travel times, interregional and multimodal connections, including waterborne and air transport (Spilanis et al., 2012; CPMR, 2002). While valuable for cross-regional comparison, these indices often overlooked qualitative service characteristics, such as vessel speed and capacities, travel cost, and reliability, neglecting variations between island and mainland connectivity (Karampela et al., 2014; Spilanis et al., 2012).

Other transport-specific measures for measuring among others connectivity, such as the Island Connectivity Index (ICI) and the Island Transport Equivalents for Passengers and Commodities (ITEP/ITEC) (Lekakou et al., 2021), extended relevant approaches incorporating travel cost, frequency, duration, service quality, and environmental and social considerations (Lekakou et al., 2021; Lekakou & Remoundos, 2018). Other frameworks, including the Liner Shipping Connectivity

Index (LSCI/LSBCI) (Hoffmann et al., 2024; Niérat & Guerrero, 2019) and the Island Dependency Index (Castanho et al., 2024), addressed freight and trade dependencies, highlighting the economic implications of transport connectivity.

Beyond transport, territorial cohesion has also been evaluated through socio-economic and structural lenses. The ESPON Insularity Index (2010) and relevant frameworks proposed by Medeiros (2011) and Garau et al. (2020) incorporated factors such as population ageing, governance capacity, and regional attractiveness, emphasizing that territorial cohesion, insularity and connectivity are only meaningful when embedded in broader socio-economic and functional contexts. Similarly, Tsekeris (2022) proposed a generalized transport cost-based index based on the indicator of Persyn et al. (2022, 2020, 2019) capturing both distance- and time-related transport burdens of islands, linking them to population size and trade patterns.

Despite this rich body of research, several gaps remain. Existing indices are often developed for national or regional contexts (i.e., Licio and Pinna, 2021, 2013; Garau et al., 2020; Teclean and Drăgan, 2020) and rarely integrated into MSP frameworks, which limits their applicability for multi-level and cross-border governance. Many approaches prioritize ecological connectivity (Podda & Porporato, 2023; Virtanen et al., 2020; Ceccarelli et al., 2018), while socio-economic and territorial cohesion, especially port-to-island accessibility and SSS performance, remain unexplored. Data heterogeneity, methodological inconsistencies, and the lack of harmonized indicators further constrain their use in comparative or transboundary contexts.

These limitations highlight the need for a systematic and transparent framework for monitoring territorial cohesion in island regions through SSS networks. Building on the insights from prior indices, this study develops two CIs that aggregate relevant KPIs, capturing both connectivity and accessibility dimensions, reflecting key structural and socio-economic characteristics of the Greek island transport system. While the empirical application is limited to the Greek domestic context, the framework is designed using generic indicators, standardized aggregation procedures, and widely available data types, allowing it to be conceptually transferable to other national and cross-border SSS settings. In this sense, it provides a methodological basis for improved harmonization, continuous monitoring, and integration into MSP processes.

Finally, the increasing complexity, volume, and heterogeneity of maritime transport and governance data motivate the conceptual integration of AI. AI can facilitate data harmonization, automate the calculation and updating of indicators, and support predictive and adaptive decision-making across multiple jurisdictions. By embedding AI into the framework conceptually, this study demonstrates how advanced analytical tools can enhance the efficiency, comparability, and scalability of territorial cohesion assessment, particularly in international and multi-regional contexts.

2.3. International cooperation in the MSP framework

MSP is widely recognized as a central governance instrument for managing competing maritime uses and advancing sustainability and territorial cohesion objectives across multiple spatial scales. Its implementation is guided by a set of core principles, among which evidence- and science-based decision-making is particularly critical for this study. This principle underpins the capacity of MSP to design effective measures, evaluate outcomes, and adapt plans over time, and it relies fundamentally on access to reliable, comparable, and up-to-date data (Keijser et al., 2018; HELCOM-VASAB, 2010). Traditional analytical tools supporting this process include observations, integrated databases, geographic information systems (GIS) (Aliouris et al., 2023), which enable spatial analysis, visualization, and documentation of maritime activities.

Another central principle of MSP is cross-border and transboundary cooperation. Since maritime uses, transport networks, and environmental processes rarely align with administrative boundaries, effective MSP requires coordination across jurisdictions to ensure coherence in planning objectives, regulatory approaches, and implementation practices (UNESCO-IOC & European Commission, 2021; Keijser et al., 2018). Cross-border cooperation supports the development of common standards, encourages knowledge transfer, and strengthens capacity building, particularly in shared sea basins (Aliouris et al., 2023; UNESCO-IOC & European Commission, 2021; Keijser et al., 2018; HELCOM-VASAB, 2010). Closely related is the principle of land-sea interaction and coherence, which underpins vertical coherence across governance levels and sectors (Enet, 2022; UNESCO-IOC & European Commission, 2021), and the need for MSP to remain an adaptive and iterative process informed by continuous monitoring and evaluation (UNESCO-IOC & European Commission, 2021; Collie et al., 2013; HELCOM-VASAB, 2010).

In practice, however, international and cross-border collaboration in MSP faces persistent operational challenges. These include differences in national planning systems, diverging policy priorities, heterogenous data sources, and inconsistencies in data collection methods and quality assurance procedures (Friess and Grémaud-Colombier, 2021; Nikkanen et al., 2018). Data exchange alone is therefore insufficient; effective cooperation depends on the harmonization, interoperability, and continuous updating of shared datasets and analytical outputs. Common data frameworks and agreed metadata standards are essential to ensure that information remains comparable and usable across borders and over time (Nikkanen et al., 2018).

Within this context, indicator-based approaches play a critical role. The use of common indicators enables comparison of territorial conditions, policy performance, and planning outcomes across regions and countries, thereby enhancing transparency and accountability in MSP (Varjopuro, 2019b; Schaefer and Barale, 2011; Backer, 2008). Indicators provide a structured means to translate complex spatial and socio-economic dynamics, such as connectivity and accessibility, into measurable metrics that can inform both national and transnational decision-making. Nevertheless, the implementation of shared indicators remains challenging, as differences persist in indicator definitions, reporting formats, metric systems, and temporal resolution (Varjopuro, 2019b). These limitations constrain the ability of MSP to support systematic cross-border monitoring and coordinated policy responses.

A number of studies have explicitly addressed these challenges by proposing frameworks for cross-border MSP monitoring and evaluation, particularly within the European context (e.g., Pastoors et al., 2012; TPEA, 2014; Carneiro, 2013; Alfaré et al., 2015; Kannen et al., 2016; Varjopuro, 2019a, 2017; Schultz-Zehden, 2021; Arndt et al., 2023). A notable example is the methodological framework developed for the Eastern Mediterranean Sea Region by Avgerinou-Kolonias et al. (2018), which links monitoring and evaluation steps to distinct MSP stages. The framework distinguishes between state indicators (baseline conditions), process indicators (planning and implementation steps), and performance indicators (outcomes and impacts), thereby a structured and transparent approach to assessing MSP effectiveness across jurisdictions (Avgerinou-Kolonias et al., 2018).

Despite these advances, existing frameworks remain heavily dependent on manual data processing and fragmented national reporting practices. As the number, volume, and heterogeneity of data sources increase, particularly in relation to transport systems such as SSS, these limitations become more pronounced. This creates a clear need for analytical approaches that can support scalable, harmonized, and continuously updated indicator-based monitoring across borders. This gap provides a conceptual bridge to the growing role of AI, which is discussed in Section 2.4 as an enabling technology capable of enhancing data harmonization, indicator alignment, and adaptive monitoring within international MSP processes.

2.4. The conceptual role of Artificial Intelligence in monitoring and evaluation

AI is increasingly recognized as a critical enabling technology for addressing the analytical and governance challenges identified in indicator-based monitoring and international cooperation within MSP. As demonstrated in Sections 2.1 – 2.3, the measurement of territorial cohesion through composite indicators and the implementation of cross-border MSP both depend on the availability of large, heterogenous, and continuously evolving datasets, as well as on the harmonization of methods, definitions, and reporting practices across jurisdictions. AI does not replace indicator-based frameworks; rather, it provides the computational and analytical capacity required to operationalize them at scale, particularly in multi-regional and transboundary contexts.

A key contribution of AI lies in its ability to automate and optimize processes that are traditionally time-consuming, labor- and resource-intensive, and prone to subjectivity when conducted manually (Manikandan et al., 2025). In this context of MSP monitoring and evaluation, this includes data ingestion, preprocessing, integration, and quality control across diverse sources such as transport schedules, port statistics, spatial datasets, and socio-economic indicators. AI-enabled marine spatial data infrastructures (MSDI), including digital ocean platforms and intelligent data services, can enhance interoperability and support systematic updates of monitoring datasets, addressing one of the main barriers to cross-border cooperation identified in the literature (Al Subhi and Al Suqri, 2025; Brunel et al., 2023).

Beyond data management, AI techniques offer targeted solutions to the cooperation and harmonization challenges discussed in Section 2.3. Natural Language Processing (NLP), for example, can support the alignment of national MSP documents, transport policies, and planning objectives by extracting, classifying, and comparing terminology, priorities, and regulatory provisions across countries. This capability is particularly relevant for regions where policy frameworks and reporting formats differ, yet comparability is required for joint monitoring and evaluations. Similarly, machine learning methods can be applied to detect patterns, inconsistencies, and gaps in indicator datasets, supporting the harmonization of divergent data-reporting standards and improving the robustness of composite indicators used to assess connectivity and accessibility.

AI also contributes to the analytical depth and adaptive capacity of the MSP monitoring systems (Manikandan et al., 2025; Guevara et al., 2025; eMSP NSBR, 2024). Predictive and forecasting models enable the assessment of future scenarios, such as changes in SSS demand, fuel consumption, or network performance, thereby supporting proactive and evidence-based planning (Al Subhi and Al Suqri, 2025; Vu et al., 2024). In parallel, computer vision and remote sensing techniques facilitate continuous environmental and activity monitoring, including the detection of maritime traffic patterns, port operations, and environmental pressures, which are essential inputs for performance evaluation within MSP cycles (Manikandan et al., 2025; eMSP NSBR, 2024).

Through these capabilities, AI offers a conceptual pathway through which indicator-based approaches to territorial cohesion, such as the CIs developed in this study, can be scaled, harmonized, and continuously updated. While AI methods are not empirically implemented in the present case study, their conceptual integration clarifies how the proposed framework could be operationalized more efficiently in future cross-border and multi-regional applications. In this sense, AI functions as a transversal enabling layer that links measurement (Sections 2.1–2.2), international cooperation (Section 2.3), and adaptive MSP implementation, thereby strengthening the relevance of national case studies as building blocks for broader international cooperation in maritime governance.

2.5. Synthesis of research gaps within the context of the case study

Despite the extensive research on island territorial cohesion, SSS connectivity, and MSP practices, the literature reveals persistent fragmentation and limitations in integrating these domains into a coherent framework. Existing approaches to measuring cohesion and accessibility provide valuable insights but remain largely nationally bounded, static, or limited to specific transport modes. Similarly, MSP research highlights the importance of cross-border cooperation and standardized indicators, yet practical harmonization across jurisdictions is rarely achieved. While AI has been increasingly proposed to support data management, monitoring, and policy analysis, its potential to align disparate national data, harmonize indicators, and operationalize cross-border monitoring frameworks has not been systematically explored.

From this synthesis, four key gaps emerge. First, cohesion and connectivity indices are rarely embedded within the MSP cycle, limiting their utility for policy evaluation and cross-border planning. Secondly, existing indices are predominantly tailored to specific national and regional contexts and lack methodological flexibility for local, geographically based (i.e., island level) applications, thereby demonstrating a transferability gap of these indices. Additionally, the continuous, indicator-based monitoring of SSS connectivity and accessibility is insufficient, constraining evidence-based decision-making. Finally, while AI can facilitate data harmonization, predictive analytics, and evidence-based decision support, its conceptual and practical integration into cross-border MSP frameworks remains underdeveloped.

This study addresses these gaps by developing two CIs that aggregate relevant KPIs to capture connectivity and accessibility dimensions while accounting for the structural and socio-economic characteristics of the Greek islands. While the proposed indicators do not resolve all limitations of previous approaches, they provide a robust, transferable framework that supports systematic assessment, evidence-based MSP, and the conceptual groundwork for future cross-border applications.

3. Methodological approach

3.1. Case study context

The Greek SSS system is a complex network serving both coastal and island ports through domestic and international connections. Domestic lines primarily link island ports with each other and the mainland, while international lines mainly connect Greece with Italy and other areas within the Adriatic Sea (Latsis, 2020). Approximately 180 island ports are served by the domestic network, which is categorized into main and local lines. Main lines provide connectivity between ports located in different administrative units (NUTS III), while local lines cover the remaining connections. Between 2017 and 2026 (planned), the total number of lines ranged from 592 in 2018 to 493 in 2026, with a sharp decline of about 19 % in 2019, after which numbers remained relatively stable (Ministerial Decision No. 2253.1-1/74032/2024; Ministerial Decision No. 2253.1-1/75342/2023; Ministerial Decision No. 2253.1-1/76240/2022; Ministerial Decision No. 2253.1-1/75649/2021; Ministerial Decision No. 2253.1-1/70759/20; Ministerial Decision No. 2253.1-1/79080/19; Ministerial Decision No. 2253.1-1/79189/18; Ministerial Decision No. 2253.1-1/77149/17; Ministerial Decision No. 2253.1-1/82937/16). This decline may be linked to revisions in the criteria or framework of the indicative SSS network by the Hellenic Ministry of Maritime Affairs and Insular Policy (MoMAIP), reflecting adjustments in national network planning.

The sector operates under a complex institutional framework designed to safeguard passenger interests by ensuring adequate safety, stability, reliability, and service quality, while simultaneously fostering economic growth and promoting cohesion across Greek island regions. SSS plays a critical role in maintaining accessibility and connectivity, thereby contributing to socio-economic and territorial cohesion among the islands and between the islands and the mainland (CERTH, 2021b). This is particularly significant given Greece's geographic and demographic profile, which includes an extensive coastline, numerous islands, and small, dispersed island populations. Economically, SSS contributes 8.9 % to the national Gross Domestic Product (GDP) and 3.1 % to Gross Value Added (GVA) (IOBE, 2023). It also supports key sectors such as agriculture, manufacturing, and tourism (IOBE, 2021; XRTC Business Consultants, 2020; EESYM et al., 2014), thereby indirectly reinforcing the national economy (IOBE, 2023).

In 2024, SSS transported approximately 40 million passengers and 143 million tonnes of goods, both domestically and internationally (ELSTAT, n.d.). Passenger traffic is highly seasonal, affecting network characteristics such as weekly frequency of itineraries and vessel size, and posing challenges to territorial cohesion, connectivity, and accessibility. According to industry data (XRTC Business Consultants, 2024), the Greek fleet comprised 155 vessels operated by 33 shipping companies in 2023, with a combined capacity exceeding 133,000 passengers and 32,000 vehicles. However, the fleet remains relatively old. In 2019, the average age was 28 years, and 35 % of the fleet was over 30 years old (PwC Business Solutions, 2019). This ageing profile negatively impacts both service quality and environmental performance, especially given EU and national environmental targets that call for near-total carbon neutrality.

Rising costs further challenge the sector. In the first half of 2024, ferry ticket prices increased by 40 % – 60 % compared with 2019 (XRTC Business Consultants, 2024), primarily due to inflation and rising expenses for fuel (9 %), spare parts (14 %), wages (24 %) and other operational needs (XRTC Business Consultants, 2024). To mitigate the burden of high ticket prices, the Transport Equivalent (TE) scheme was introduced in 2019, aiming to equalize travel costs between mainland-to-island and inter-island journeys with those for comparable distances on the mainland (Transport Equivalent, n.d.). Additionally, many SSS routes operate under Public Service Obligations (PSOs), which set minimum service frequencies and vessel standards according to the capabilities of local port infrastructures, especially in small island ports with limited facilities.

This case study focuses specifically on passenger transportation via domestic SSS lines. While the present analysis is limited to the Greek domestic context, the methodological framework is designed to be transferable to other settings, including cross-border connections. As such, it supports efforts towards data harmonization, which is a critical prerequisite for fostering international cooperation within the frameworks of MSP and related governance processes. Additionally, the comprehensive dataset of the Greek SSS system provides a basis for potential AI-supported analyses, including automated KPI calculation, predictive modelling, and scenario-based assessment of connectivity and accessibility.

3.2. Theoretical framework of the composite indicators, key performance indicators selection and data sources

Territorial cohesion is influenced by multiple socio-economic and geographic factors linked to competitiveness, connectivity, accessibility, and attractiveness. This case study, however, narrows its scope to the interrelationship between territorial cohesion and SSS. It forms part of a broader research effort aimed at measuring territorial cohesion across several dimensions, namely connectivity, accessibility, environmental performance, socio-economic and technological factors, and governance, through the integration of these dimensions into a composite indicator. For the purpose of this case study, the KPI framework concentrates specifically on the dimensions of connectivity and accessibility.

The connectivity dimension captures the structure and efficiency of the SSS network in linking islands with each other and with the mainland. Its conceptual foundation draws on UNCTAD's Liner Shipping Connectivity Index (LSCI) (Hoffmann et al., 2024; Niérat & Guerrero, 2019), adapted here to the context of passenger transport via SSS. The accessibility dimension, while closely linked to connectivity and therefore challenging to disentangle, reflects how easily and effectively passengers can travel from and to Greek islands, as well as the extent to which transportation needs are met by the services provided. In this study, accessibility is approached primarily as a measure of service quality in terms of distance, time, and ticket cost.

The KPIs were selected following a review of relevant literature on CIs for connectivity and accessibility, ensuring alignment with established practices while tailoring them to the SSS context. This selection was further guided by data-related considerations. The availability and reliability of data, the analytical soundness of the indicators, and their timeliness, in accordance with selection criteria outlined by OECD, EU, and JRC (2008). The chosen geographic reference unit was island, defined as *'a naturally formed area of land surrounded by water, which is above water at high tide'* (UNCLOS - United Nations, 1994).

The primary data source was the Integrated Database of the Short Sea Shipping Network (EVDAD), developed by the Centre for Research and Technology Hellas (CERTH) with funding from the MoMAIP. This database consolidates information from multiple sources, including the System for Booking Seats and Issuing Passenger Tickets and Vehicle Transport Receipts (for shipping businesses) (HSKTHEEA), the Hellenic Statistical Authority (ELSTAT), MoMAIP, geodata.gov, and OpenStreetMap (OSM). It provides detailed data on scheduled itineraries, departure and arrival times and ports, issued tickets, passenger and vehicle traffic per port, operating vessels and their characteristics, the overall network structure, travel distances, and ticket prices. Certain variables, such as travel distances and tickets prices, contain missing values that required appropriate handling. The database includes historical records for 2018 – 2024 and is updated annually through automated data-entry processes to incorporate the latest information. Certain fields contain missing values, which are addressed through data imputation methods detailed in Section 3.3.

For this case study, KPIs were calculated for the year 2018, selected as a baseline reference. This year was selected deliberately to precede the disruptions caused by the Covid-19 pandemic, thus providing a stable benchmark against which subsequent development can be compared. Thus, the proposed methodological framework is designed to be transferable to other years and settings, including cross-border connections, supporting harmonization and comparability while maintaining a focus on connectivity and accessibility.

3.3. Composite indicators development

The dimensions of connectivity and accessibility were synthesized into CIs following the methodological guidelines of OECD, EU, and JRC (2008). The purpose of these indicators is to enable meaningful comparison among the Greek islands and to support evidence-based, data-driven policymaking, ensuring that interventions can be prioritized effectively.

At the outset, several candidate KPIs were identified for potential integration into the measurement framework of both dimensions. These KPIs were first explored through descriptive statistics to better understand the dataset, identify patterns, and determine the appropriate treatment of issues such as missing values.

The finalized CI and KPI framework, including the definitions and calculation formulas, are presented in Table 1, while the underlying data structure of the EVDAD database used for the calculation is summarized in Table 2.

Following the initial data exploration, several KPIs (i.e., SI4, SI5, SI6, SI7) contained missing values requiring data imputation. A combination of deterministic reconstruction, rule-based imputation, and single-value imputation was applied depending on the nature of each indicator and data availability, ensuring completeness while maintaining transparency and reproducibility.

For passenger capacity (SI4), missing values were first enriched using alternative data sources, and the remaining gaps were filled using single-value mean imputation based on the average Greek ferry fleet capacity (766 passengers). This pragmatic approach was necessary due to the lack of detailed vessel characteristics (i.e., length, breadth, type, etc.)

Table 1
Key performance indicator framework with definitions.

ID	Indicator	Definition
CI1 Connectivity		
SI1	Direct connections	$SI1_i = \sum_j x_{ij}$ where x_{ij} represents the number of direct connections from island *i* to island *j*. Higher values indicate better connectivity.
SI2	Port calls	$SI2_i = \sum x_i$ where x_i is the total number of port calls for island *i*. Higher values indicate stronger connectivity.
SI3	Unique vessels	$SI3_i = \sum x_i$ where x_i represents the total number of unique vessels serving island *i*. Higher values indicate better connectivity.
SI4	Passenger capacity	$SI4_j = \frac{1}{n_j}\left(\sum_{i=1}^{n} x_{i,j}\right)$ where $x_{i,j}$ is the average passenger capacity per itinerary of vessel *i* operating itineraries from or to island *j*; and n_j is the number of itineraries serving island *j*. Higher values indicate better connectivity.
CI2 Accessibility		
SI5	Estimated travelled distance	$SI5_i = \frac{1}{n_i}\left(\sum_{j=1}^{n_i} x_{i,j}\right)$ where $x_{i,j}$ is the nautical miles of realized itineraries from port *i* to port *j*, including transit legs; and *n* is the number of itineraries. Lower values indicate better accessibility.
SI6	Estimated travel time	$SI6_j = \frac{\sum_{i=1}^{n_j}\left(x_{i,j} * y_{i,j}\right)}{\sum_{i=1}^{n_j} y_{i,j}}$ where $x_{i,j}$ is the travel time from port *i* to port *j*, considering transit legs, and given in minutes; $y_{i,j}$ is the frequency of route *ij* for the specific time interval; and *n* is the total number of unique routes *ij*. Lower values indicate better accessibility.
SI7	Estimated ticket price	$SI7_i = \frac{1}{n_i}\left(\sum_{j=1}^{n_i} x_{i,j}\right)$ where $x_{i,j}$ is the estimated ticket price for travelling from port *i* to port *j*, considering transit legs, and given in euros (€); and *n* is the total number of unique routes *ij*. Lower values indicate better accessibility.

Source: authors' own elaboration

Table 2
EVDAD database fields used in the case study.

Table	Field	Description
Tickets	Date/Time	Scheduled departure date and time of the ticket.
	Route	Full route to which the line leg, for which the ticket was issued, is attributed.
	Port of departure	Departure port.
	Port of arrival	Arrival port.
	Operating vessel	Vessel assigned to the itinerary.
Vessel	Vessel identifier	Vessel identifiers (IMO, MMSI).
	Winter passenger capacity	Winter passenger capacity of the operating vessel.
	Summer passenger capacity	Summer passenger capacity of the operating vessel.
Network	Line leg travel distance	Travelled distance of the ticket calculated via GIS.

Source: authors' own elaboration on data from EVDAD.

that would allow for more sophisticated imputation techniques. While this method may introduce systematic bias and reduce variance, it ensures dataset completeness and consistent treatment across the islands.

For estimated travelled distance (SI5), partial data provided by the MoMAIP were complemented through GIS-based calculations to create a port-to-port distance index reflecting realized itineraries, including transit legs. Estimated travel time (SI6) was derived from the scheduled departure times of the realized itineraries, generating a frequency-weighted port-to-port travel time index. For estimated ticket price (SI7), the missing entries were imputed using a rule-based approach, applying an average cost per nautical mile (0.31€) multiplied by the corresponding travelled distance. This method reflects prevailing pricing structures in the Greek SSS system but may underrepresent fare heterogeneity related to service type, seasonality, and vessel characteristics.

Overall, this imputation strategy prioritizes transparency, reproducibility, and consistency across islands, while acknowledging the increased uncertainty and potential bias in SI4 and SI7. These limitations are considered in the interpretation of results and policy implications.

Following data imputation, descriptive statistics were recalculated, and the KPIs were aggregated at the island level. A Pearson correlation analysis was applied to raw KPI values to assess statistical dependencies, supporting the KPI selection, and informing subsequent methodological steps, particularly normalization and weighting. The results indicated predominantly weak to moderate associations among most KPIs, with strong correlations appearing only among accessibility KPIs (distance, time, price), which belong to the same conceptual dimension and therefore do not justify differential weighting across dimensions.

The KPIs were then normalized using the Min-Max method, rescaling each KPI to range between 0 and 1. While this method facilitates comparison, ranking, benchmarking, and aggregation of KPIs, it is sensitive to extreme values and outliers (OECD, EU & JRC, 2008). Given the presence of outliers and skewed distributions, additional normalization methods were applied as robustness checks, including (a) Z-score standardization, which is less sensitive to extreme values than Min-Max; and (b) robust scaling normalization that is based on the median and interquartile range, highly robust to outliers and skewed distributions.

The formulas used for each normalization method were according to Eqs. (1)–(6). Min-max normalization is given by Equation (1), where x is the original value of the KPI, x' the normalized value of the KPI, $\min(x)$ the minimum observed value, and $\max(x)$ the maximum observed value. For KPIs with a negative impact on the CIs, values were reversed using Equation (2).

$$x' = \frac{x - \min(x)}{\max(x) - \min(\mathrm{x})} \tag{1}$$

$$x^{'} = 1 - \frac{x - \min(x)}{\max(x) - \min(\mathrm{x})} \tag{2}$$

The Z-score standardization is calculated using Equation (3), where x is the raw score, μ is the mean of the population, and σ the standard deviation of the population. For KPIs with negative impact on the CIs, values were reversed using Equation (4).

$$z = \frac{x - \mu}{\sigma} \tag{3}$$

$$z^{'} = -z \tag{4}$$

The robust scaling normalization is based on Equation (5), where x is the original value, Median(x) is the median quartile, and IQR is the interquartile range, thus the difference between the 75th percentile (Q3) and the 25th percentile (Q1) of the dataset. KPIs with negative impact on the CIs were reversed using Equation (6).

$$x' = \frac{x - \mathrm{Median(x)}}{\mathrm{IQR}} \tag{5}$$

$$x^{'} = -\frac{x - \mathrm{Median(x)}}{\mathrm{IQR}} \tag{6}$$

The normalized values were compared through robustness checks, implemented through pairwise Spearman rank correlations analyses to identify the degree to which the results are differentiated across the alternative normalization methods.

For weighting, an equal-weighting approach was chosen, as the correlation analysis indicated no statistical dependencies requiring different weighting (Nardo et al., 2005; Gan et al., 2017; Greco et al., 2019; Pereira Libório et al., 2023), and all parameters represent equally important dimensions of connectivity and accessibility. Moreover, literature provides no empirical evidence supporting the prioritization of any specific dimension over the others (Shi and Land, 2021). Additionally, equal weighting minimizes subjective bias and enhances transparency and replicability (Beaverstock et al., 1999; Jiang and Shen, 2013; Becker et al., 2017; Gan et al., 2017; Talukder et al., 2017; Greco et al., 2019; Terzi et al., 2021; Pereira Libório et al., 2023; D'Adamo et al., 2025; UNECE, 2025), which is particularly valuable when interpreting CI results for policy-making purposes. The sum of the weights for the KPIs within each CI equals 1. Aggregation was conducted by calculating the weighted arithmetic mean, consistent with the equal-weighting assumption (OECD, EU & JRC, 2008). To confirm the robustness of the CI results to the choice of normalization method, Spearman rank correlations were calculated for the KPIs across Min-Max, Z-score, and robust scaling normalization. The correlations were equal to 1 for all KPIs, indicating that the relative rankings of islands are identical regardless of the normalization method. Therefore, the CI values are robust, and the final presentation uses the Min-Max normalized KPIs. The resulting CI values were again normalized using the Min-Max method.

Within this methodological framework, AI is conceptually integrated as an enabling layer supporting data preparation, consistency checks, scalability, and reproducibility of the CI framework. AI-based tools, such as machine learning for anomaly detection and pattern recognition, can assist in identifying irregularities in large transport datasets and in automating data imputation processes. NLP can aid the harmonization of data, metadata, and indicator definitions across jurisdictions. AI-assisted clustering may support the identification of connectivity and accessibility patterns, enhancing policy formulation for islands with similar characteristics. While AI is not directly used to compute the CIs in this case study, its integration improves the transferability and future applicability of the framework in cross-border MSP contexts.

Finally, the two CIs are ultimately expressed as coordinates, with CI1 plotted on the X-axis and CI2 on the Y-axis. This visualization allows for the identification of island clusters and outliers, supporting data-driven prioritization of interventions, whether connectivity- or accessibility-oriented, and at the level of individual islands or groups. The approach highlights relative strengths and weaknesses without imposing normative thresholds, which are further examined in the results and robustness analysis.

4. Insights from the Greek short sea shipping case study

4.1. Data exploration

The EVDAD database includes 88 islands, of which only 72 recorded passenger traffic in 2018. This suggests that the remaining 16 islands (Agios Georgios, Ammouliani, Antiparos, Elafonisos, Ereikoussa, Kalamos, Kastos, Kinaros, Levitha, Mathraki, Marathi, Meganisi, Othonoi, Salamina, Trizonia, and Farmakonisi) may have been connected through SSS services without tickets being issued during that year.

Descriptive statistics were applied twice, as some KPIs contained missing values that required imputation, applied as described in Section 3.3. Following the imputation of missing values, a second round of descriptive statistics was conducted. The results are summarized in Table 3.

Almost all KPIs exhibited outliers, prompting a closer inspection of the dataset to determine whether corrections or adjustments were required.

To address the presence of outliers, the data were systematically examined to distinguish between genuine extreme values that reflect real-world conditions (i.e., usual high seasonal passenger flows) and potential data anomalies or errors. Outliers confirmed as accurate representation of actual conditions were retained to preserve the variability of the dataset, while those identified as likely errors were cross-checked against original sources.

To examine statistical dependencies among KPIs, a Pearson correlation analysis was conducted (Table 4). Connectivity-related KPIs (SI1 – SI4) display moderate correlations, suggesting partial co-variation but no complete redundancy. Among accessibility KPIs (SI5 – SI7), very strong correlations exist between estimated travelled distance (SI5), estimated travel time (SI6), and ticket price (SI7), reflecting their inherent interdependence.

Overall, the correlation analysis suggests that while some indicators are highly interdependent, these relationships reflect conceptually related aspects rather than redundancy across dimensions. This justifies the use of an equal-weighting scheme for the aggregation of connectivity and accessibility KPIs.

The imputation strategies for SI4 and SI7 introduce a potential risk of

Table 4
Pearson correlation coefficients among the KPIs of the Greek islands (values before normalization and after imputation of missing values).

	SI1	*SI2*	*SI3*	*SI4*	*SI5*	*SI6*	*SI7*
SI1	1.000						
SI2	0.363	1.000					
SI3	0.673	0.575	1.000				
SI4	0.309	0.039	0.450	1.000			
SI5	0.114	−0.288	0.063	0.638	1.000		
SI6	0.039	−0.328	−0.044	0.563	0.968	1.000	
SI7	0.103	−0.318	0.070	0.617	0.986	0.958	1.000

Source: authors' own elaboration.

Table 3
Descriptive statistics of KPIs (after imputation).

Statistical measure	Value						
	SI1	SI2	SI3	SI4	SI5	SI6	SI7
Mean	6.11	1,881.69	10.67	798.80	49.28	196.90	16.19
Standard Error	0.61	254.44	0.91	32.90	3.77	14.79	1.06
Median	4.50	1,148.00	9.00	738.17	41.78	167.10	14.45
Mode	3.00	#N/A	9.00	#N/A	#N/A	#N/A	#N/A
Standard Deviation	5.75	2,158.99	7.70	279.16	32.03	125.54	9.04
Sample Variance	33.11	4,661,240.00	59.27	77,930.57	1,025.67	15,760.02	81.65
Kurtosis	0.84	6.70	1.73	0.64	5.29	4.37	4.93
Skewness	1.13	2.43	1.37	0.73	1.86	1.83	1.65
Range	26.00	10,854.00	35.00	1,425.24	185.27	681.88	54.02
Minimum	0.00	29.00	1.00	180.00	6.64	32.38	2.85
Maximum	26.00	10,883.00	36.00	1,605.24	191.91	714.26	56.87
Sum	538.00	135,482.00	768.00	57,513.48	3,548.21	14,176.75	1,165.64
Count	88.00	72.00	72.00	72.00	72.00	72.00	72.00
Confidence Level (95.0 %)	1.22	507.34	1.81	65.60	7.53	29.50	2.12
Lower Outlier	−11.15	−4,595.28	−12.43	−38.68	−46.80	−179.72	−10.92
Upper Outlier	23.38	8,358.67	33.76	1,636.28	145.36	573.52	43.30

Source: author's own elaboration.

systematic bias, which should be considered when interpreting the results and deriving policy recommendations. Additionally, the presence of outliers and skewed distributions warranted the application of robustness checks.

4.2. KPIs calculations and ranking of the islands

Following the data exploration process, the KPIs were calculated, normalized, weighted, and aggregated into the CIs using the equations presented in Section 3. The CIs were also normalized and the results for equal weighting of both KPIs and CIs are summarized in Table 5. The 16 islands identified as not connected in 2018 are excluded from the analysis.

For direct connections (SI1), Crete ranks first with 23 connections, largely due to its size, economic significance, and its 11 operational ports, many of which are interconnected. Crete's role as a strong regional economy attracts not only tourists but also passengers traveling for business and trade purposes. Similarly, other economically significant or strategically located islands demonstrate high connectivity (i.e., Samos 3rd, Kos and Chios 4th rank, Naxos and Patmos 8th rank, etc.). Geographic positioning is also decisive. Islands located along main shipping corridors or surrounded by smaller islands are more easily

Table 5

Results of normalized KPIs and CIs for each Greek island according to the equal weighting method.

Island	SI1	SI2	SI3	SI4	SI5	SI6	SI7	CI1	CI2
Aegina	0.2727	0.8285	0.3429	0.4395	0.9947	1	0.989	0.6733	0.9969
Agathonisi	0.1818	0.0493	0.0857	0.1961	0.7953	0.7839	0.7577	0.1694	0.7808
Agios Efstratios	0.0909	0.0224	0.0286	0.4365	0.5998	0.5391	0.6455	0.1934	0.5962
Agistri	0.0909	0.2321	0.1714	0.3838	0.9607	0.9876	0.9509	0.3037	0.9686
Alonnisos	0.4091	0.0782	0.2286	0.3975	0.901	0.8684	0.8488	0.3901	0.8747
Amorgos	0.5455	0.0974	0.3714	0.4657	0.7913	0.7732	0.735	0.5249	0.7683
Anafi	0.2727	0.0242	0.2286	0.6468	0.5546	0.5127	0.4926	0.4118	0.5212
Andros	0.1818	0.2127	0.4	0.6868	0.7928	0.7881	0.7802	0.5254	0.7888
Antikythera	0.0909	0.0161	0.0286	0.2957	0.7605	0.6916	0.7594	0.1394	0.7389
Arkoi	0.0909	0.0276	0.0857	0.1646	0.8703	0.8694	0.8383	0.1164	0.8613
Astypalaia	0.2727	0.0302	0.1429	0.7663	0.536	0.5802	0.533	0.4264	0.5510
Chios	0.7273	0.1568	0.3429	0.6513	0.6349	0.6252	0.6695	0.6713	0.6447
Corfu	0.0909	0.8996	0.5714	0.3032	0.9505	0.9353	0.943	0.6665	0.9451
Crete	1	0.6081	0.7429	0.4214	0.6401	0.6135	0.6494	1	0.6358
Donousa	0.1364	0.0452	0.2286	0.5067	0.8133	0.7959	0.7869	0.3179	0.8005
Evia	0.5	1	0.3714	0.3444	0.9624	0.9466	0.9569	0.7954	0.9575
Folegandros	0.3636	0.1102	0.3429	0.2893	0.7522	0.7773	0.7038	0.3874	0.7461
Fournoi	0.5	0.0797	0.2857	0.5528	0.8694	0.8481	0.8638	0.5022	0.8624
Gavdos	0.1364	0.0169	0.0286	0.1357	0.8582	0.648	0.7626	0.0975	0.7580
Halki	0.0909	0.0328	0.0857	0.4349	0.5788	0.5236	0.5496	0.2177	0.5519
Hydra	0.1818	0.2398	0.2	0.183	0.9064	0.9364	0.889	0.2766	0.9127
Ikaria	0.5909	0.0716	0.3143	0.8443	0.6167	0.6348	0.601	0.6503	0.6189
Ios	0.3182	0.2499	0.6571	0.5806	0.7274	0.764	0.6866	0.6447	0.7277
Irakleia	0.0909	0.0634	0.1714	0.3636	0.8834	0.8549	0.831	0.2342	0.8584
Ithaca	0.2273	0.1406	0.0571	0.2857	0.9117	0.8481	0.8943	0.2421	0.8867
Kalymnos	0.7273	0.3137	0.3714	0.2439	0.8592	0.9073	0.8617	0.5897	0.8781
Karpathos	0.1818	0.0651	0.1429	0.4926	0.4494	0.3566	0.4309	0.3052	0.4133
Kasos	0.0909	0.041	0.0286	0.3084	0.6177	0.5266	0.5963	0.1532	0.5815
Kea	0.0455	0.0917	0.1714	0.4806	0.9074	0.889	0.8793	0.2709	0.8940
Kefalonia	0.1818	0.4	0.2	0.3772	0.9132	0.9006	0.8982	0.4069	0.9061
Kimolos	0.1818	0.0537	0.2	0.4257	0.8342	0.8038	0.8211	0.2974	0.8216
Kos	0.7273	0.362	0.4571	0.3075	0.8215	0.9039	0.8282	0.6624	0.8532
Koufonisi	0.1818	0.0965	0.2857	0.3773	0.8639	0.8489	0.818	0.3269	0.8455
Kythira	0.2727	0.0572	0.0286	0.2237	0.8209	0.7729	0.8297	0.1949	0.8097
Kythnos	0.2273	0.0817	0.2571	0.4787	0.836	0.8042	0.8157	0.3649	0.8205
Lefkada	0.0455	0.0067	0	0	0.7763	0.7312	0.7595	0	0.7574
Leipsoi	0.3636	0.1088	0.2	0.306	0.7991	0.8438	0.7837	0.3405	0.8107
Lemnos	0.4091	0.0621	0.1143	0.634	0.3195	0.226	0.3812	0.4291	0.3096
Leros	0.4091	0.1708	0.2857	0.3527	0.8302	0.863	0.8181	0.4287	0.8390
Lesvos	0.0909	0.0623	0.2286	1	0.2803	0.2162	0.3575	0.4888	0.2853
Megisti	0	0.0088	0.1429	0.9687	0	0	0	0.3927	0

(*continued on next page*)

Table 5 (*continued*)

Island	SI1	SI2	SI3	SI4	SI5	SI6	SI7	CI1	CI2
Milos	0.2727	0.1405	0.3143	0.3892	0.7338	0.7338	0.7147	0.3913	0.7291
Mykonos	0.6364	0.3881	1	0.6719	0.7286	0.7564	0.7042	0.972	0.7314
Naxos	0.6818	0.3987	0.7714	0.6654	0.7638	0.8011	0.726	0.9063	0.7654
Nisyros	0.0909	0.0674	0.2	0.3825	0.7181	0.7647	0.7013	0.2532	0.7297
Oinousses	0.0455	0.036	0.1143	0.3975	0.8349	0.8334	0.8583	0.1989	0.8441
Paros	0.4091	0.3773	0.7143	0.7797	0.7277	0.7486	0.7021	0.8191	0.7278
Patmos	0.6818	0.1209	0.3429	0.4242	0.7301	0.781	0.7179	0.5579	0.7447
Paxos	0.0909	0.1264	0.2857	0.2001	0.8656	0.8537	0.8701	0.2393	0.8651
Poros	0.0455	0.2181	0.2857	0.26	0.9057	0.9348	0.8856	0.2783	0.9108
Psara	0.1818	0.0423	0.1429	0.3388	0.7599	0.8066	0.7756	0.2403	0.7825
Pserimos	0.0909	0.0125	0.0571	0.2981	1	0.9931	1	0.1494	1
Rhodes	0.5	0.1545	0.4857	0.4871	0.6725	0.5587	0.6612	0.5791	0.6323
Samos	0.7727	0.1112	0.4571	0.7176	0.5534	0.5559	0.5314	0.7376	0.5482
Samothrace	0	0.0414	0.1143	0.2861	0.8793	0.8906	0.8526	0.1432	0.8762
Schoinoussa	0.0909	0.0632	0.2	0.3691	0.8864	0.8552	0.8295	0.2467	0.8590
Serifos	0.3636	0.1217	0.2286	0.3939	0.8254	0.8374	0.8286	0.3881	0.8324
Sifnos	0.2727	0.1665	0.2571	0.3703	0.7826	0.8048	0.7736	0.3729	0.7888
Sikinos	0.0455	0.0612	0.2286	0.3851	0.7769	0.7832	0.7114	0.2456	0.7589
Skiathos	0.5909	0.2003	0.2286	0.4193	0.8899	0.8595	0.8577	0.5099	0.8710
Skopelos	0.7273	0.2125	0.2571	0.4094	0.913	0.8828	0.893	0.5714	0.8983
Skyros	0.0455	0.0358	0	0.1256	0.8598	0.7733	0.8168	0.0569	0.8185
Spetses	0.1364	0.1427	0.1714	0.1746	0.8412	0.8689	0.8032	0.2106	0.8397
Symi	0.2727	0.1509	0.4	0.3253	0.8438	0.8488	0.8471	0.4032	0.8485
Syros	0.5455	0.2086	0.6857	0.7807	0.65	0.6701	0.6201	0.7971	0.6482
Thasos	0.0909	0.3451	0.2286	0.3749	0.9818	0.9485	0.9938	0.363	0.9769
Thira	0.9091	0.326	0.9143	0.6219	0.6188	0.6611	0.5901	0.9996	0.6248
Thirasia	0.0909	0	0.0571	0.3523	0.7179	0.7238	0.6212	0.1648	0.6892
Thymaina	0.0909	0.0343	0.0286	0.3894	0.9898	0.9512	0.9922	0.1805	0.9800
Tilos	0.1818	0.045	0.1714	0.5309	0.6594	0.6688	0.6482	0.3224	0.6603
Tinos	0.4091	0.3763	0.7429	0.6866	0.8073	0.8242	0.7915	0.7951	0.8095
Zakynthos	0.0909	0.2489	0.1714	0.4992	0.919	0.9149	0.9008	0.3523	0.9137

Source: authors' own elaboration.

integrated into routes (i.e., Thira 2nd rank, Kalymnos and Skopelos 4th rank, Ikaria and Skiathos 11th rank, etc.). Tourism adds another layer of importance, with Thira, Naxos, and Mykonos ranking high due to strong seasonal demand. In contrast, smaller or sparsely located islands, as well as those very close to the mainland, show fewer connections (i.e., Paxos, Halki, Oinousses, Megisti, Karpathos, Kasos).

Results for port calls (SI2) show significant heterogeneity. Islands close to the mainland record extremely high values, such as Evia (1st with 10,889 calls), Corfu (2nd with 9,793 calls), and Aegina (3rd with 9,022 calls). Larger islands acting as regional hubs and popular tourist destinations also rank high (i.e., Crete 4th, Naxos 6th, Mykonos 7th, etc.). Conversely, distant or smaller islands register low figures such as Gavdos (67th, 212 calls), and Thirasia (72nd, 29 calls). Lefkada (71st, 102 calls) is a notable case, explained by its bridge connection to the mainland and limited ferry operations. Islands ranking below 45th (<730 port calls) are served by fewer than one itinerary per day, including return trips.

Unique vessels (SI3) and thus the number of vessels serving each island also varies considerably. Mykonos leads with 36 vessels, followed by other popular Cycladic destinations (i.e., Thira 2nd with 33 vessels, Naxos 3rd with 28 vessels, Tinos 4th with 27 vessels, etc.) and large economic hubs such as Crete and Corfu. Smaller islands with limited services rank lower with Lefkada and Skyros being served by only one vessel each.

Passenger capacity (SI4) displays relatively normal distribution but with significant differences among islands. Lesvos ranks first, with an average per itinerary capacity of 1,605 passengers, despite scoring lower on other connectivity KPIs (SI1, SI2, SI3). This reflects the deployment of large capacity vessels covering fewer routes. Similarly, Megisti ranks 2nd (1,560), as it is served by routes designed for higher-demand destinations. Popular Cycladic islands such as Syros, Paros, and Naxos also rank highly. At the lower end, islands like Hydra, Gavdos, Skyros, and Lefkada are served mainly by smaller vessels with capacities below 450 passengers.

Fig. 1 illustrates the normalized results of SI1 – SI4, ranging from 0 (low connectivity, white color) to 1 (high connectivity, dark red color). Ports are represented by small points and the SSS network of 2018 with lines. They are included to enable the interpretation of the results.

For estimated travelled distance (SI5), most islands score above the midpoint (0.5), although extreme long-distance routes drag down rankings for some (i.e., Karpathos 69th, Lemnos 70th, Lesvos 71st, Megisti 72nd) with values exceeding 100 nm. By contrast, Pserimos ranks first (6 nm), reflecting its limited but short-range connections. Similarly, Thymaina ranks 3rd (8 nm).

Results of estimated travel time (SI6) broadly mirror SI5, though some anomalies emerge. Megisti, for example, ranks 72nd with an extreme average travel time of 714 min. Pserimos and Thymaina again show usually high scores, explained by their few but short itineraries.

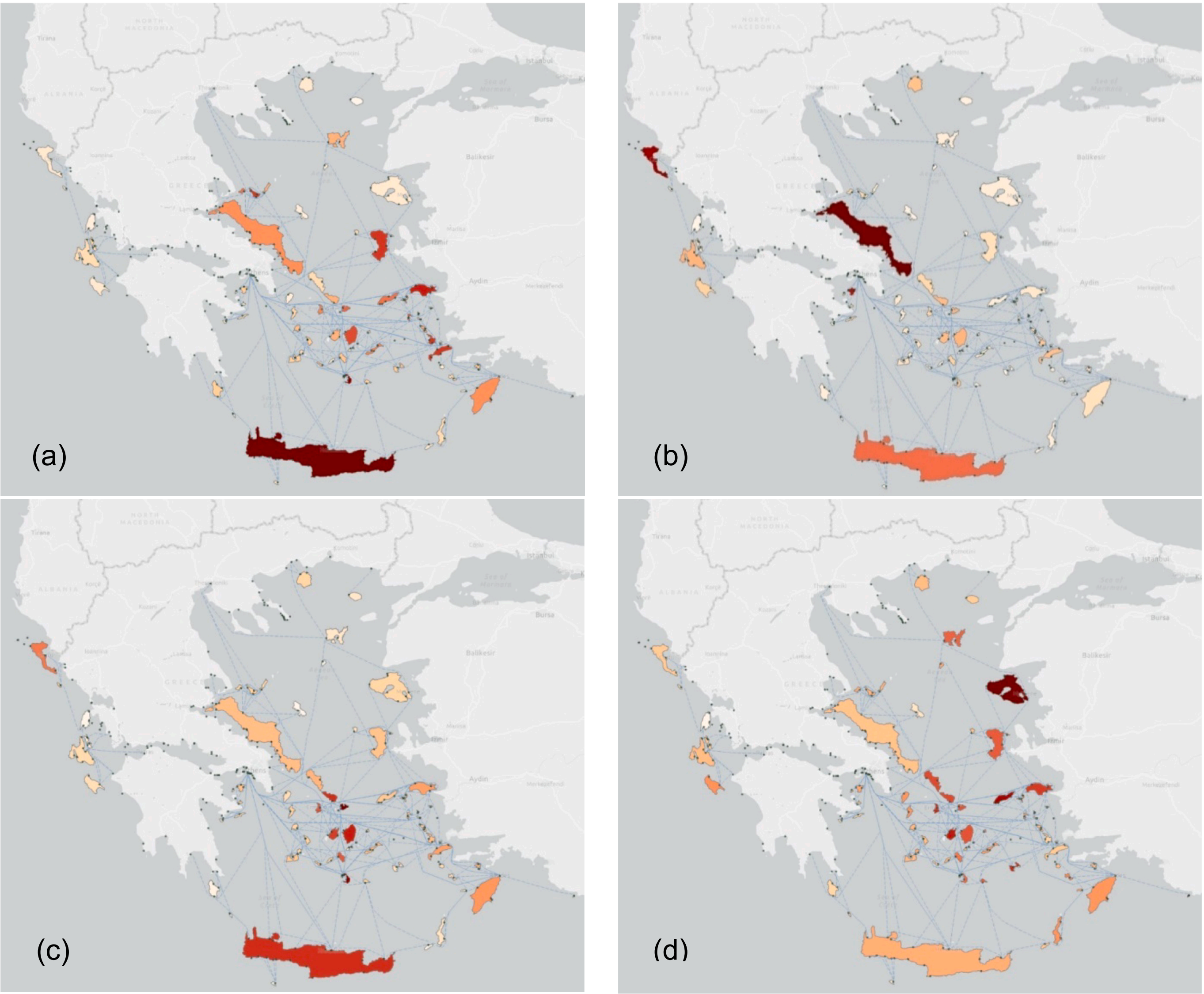

Fig. 1. Cartographic representation of normalized results of SI1 (a), SI2 (b), SI3 (c), and SI4 (d) (Source: authors' own elaboration on data).

Estimated ticket price (SI7) patterns align closely with SI5 and SI6. Pserimos ranks first (2.85€), reflecting short, low-cost trips, while Megisti ranks last (56.87€), owing to long distances and limited service.

Fig. 2 illustrates the normalized results of SI5 – SI7, ranging from 0 (low accessibility, white color) to 1 (high accessibility, dark red color). The rest of the symbology aspects are the same of Fig. 1.

The raw values were normalized applying alternative methods, Z-score standardization and Robust scaling normalization, with the detailed results summarized in Table S1 of the Supplementary Materials. Across all methods, the patterns of island performance are largely consistent, indicating that the relative ranking of islands is robust to the choice of normalization.

For connectivity KPIs (SI1 – SI4), larger islands and major tourist destinations, such as Crete, Thira, and Mykonos, consistently achieve the highest scores, while smaller and more remote islands, such as Megisti, Karpathos, and Lemnos, score lowest. Similarly, accessibility KPIs (SI5 – SI7) follow comparable trends, with islands near hubs generally performing better, despite some exceptions caused by double or triple insularity.

Robustness to normalization was assessed by computing Spearman rank correlations for each KPI across the different normalization methods (Min-Max, Z-score, Robust scaling). The detailed results are available in Table S2 of the Supplementary Materials. The results among the three normalization methods for each KPI exceed 0.95 in all cases, further confirming that the relative ranking of islands is largely dependent of the normalization method applied. This indicates that the observed patterns are robust and that Min-Max normalization, used in the main analysis, provides results consistent with other common standardization approaches.

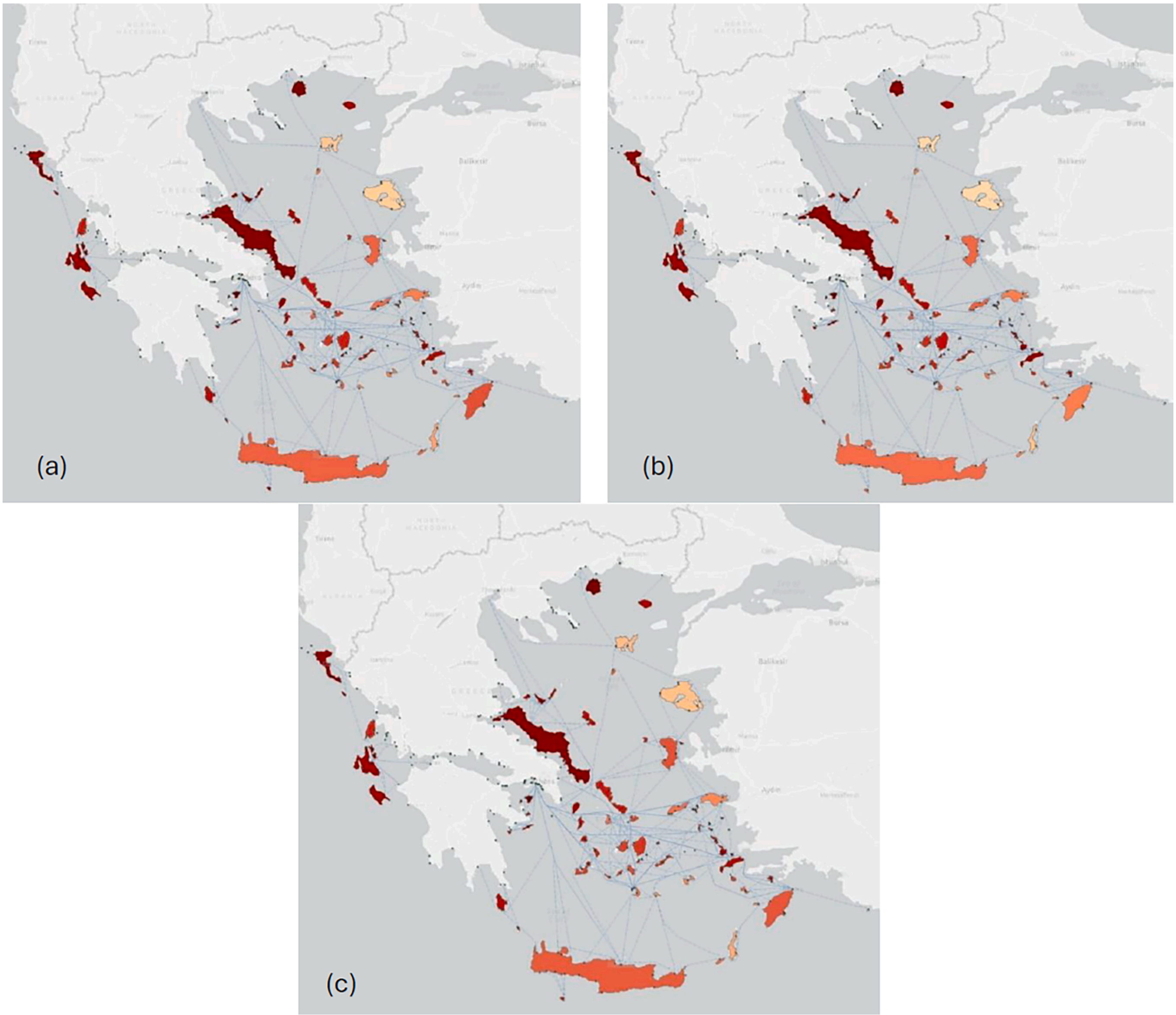

Fig. 2. Cartographic representation of normalized results of SI5 (a), SI6 (b), and SI7 (c) (Source: authors' own elaboration on data).

4.3. Aggregation in CIs and policy information

The overall connectivity index (CI1) shows Crete ranking first, with consistently high scores across all connectivity KPIs (SI1 – SI4). In total, 23 islands scored above the midpoint threshold (0.5). These include (a) popular tourist destinations, especially in the Cyclades (i.e., Thira, Mykonos, Naxos, Paros, Syros, Tinos, Ios, Andros and Amorgos in descending order); (b) large islands with strong regional economies and relatively high populations (i.e., Samos, Chios, Corfu, Kos and Rhodes in descending order); and (c) islands functioning as service hubs or strategically located along shipping routes (i.e., Ikaria, Kalymnos, Skopelos, Patmos, Skiathos and Fournoi in descending order).

The remaining 49 islands scored below the average, most of them small and suffering from double or triple insularity. According to the current institutional framework (Ministerial Decision No. 2253.1-1/74032/2024), NUTS III island ports that serve as administrative seats should be connected to the mainland via at least one shipping line operating three times per week. Other island ports should ensure connections to the NUTS III seat at least three times weekly (directly or through transit) and at least once weekly to the NUTS III seat of the region. Fig. 3 illustrates the normalized results of CI1, ranging from 0 (low overall connectivity, white color) to 1 (high overall connectivity, dark red color). Symbology aspects follow those of Figs. 1 and 2.

The accessibility index (CI2) indicates that 68 of the 72 islands perform above average. Accessibility largely mirrors the patterns observed in the underlying KPIs. The few lower-ranking islands are mainly affected by double and triple insularity, which increase travel distances and times, and passenger transport costs. Fig. 4 illustrates the normalized results of CI1, ranging from 0 (low overall connectivity, white color) to 1 (high overall connectivity, dark red color), following all symbology formats of previous maps of this study.

The combined results for CI1 and CI2 are illustrated in Fig. 5, which supports policy-oriented decision-making through a quadrant analysis. Policy quadrant assignments use a 0.5 threshold for CI1 and CI2, chosen for interpretative clarity; results are consistent across normalization methods, and alternative thresholds would not affect the main conclusions. Quadrant A (QA, lower left) includes the islands that require interventions to improve both connectivity and accessibility. Quadrant B (QB, lower right) contains the islands that need to primarily improve their accessibility. Quadrant C (QC, upper right) summarizes the islands with above-average performance in both dimensions, where no immediate interventions are necessary. Quadrant D (QD, upper left)

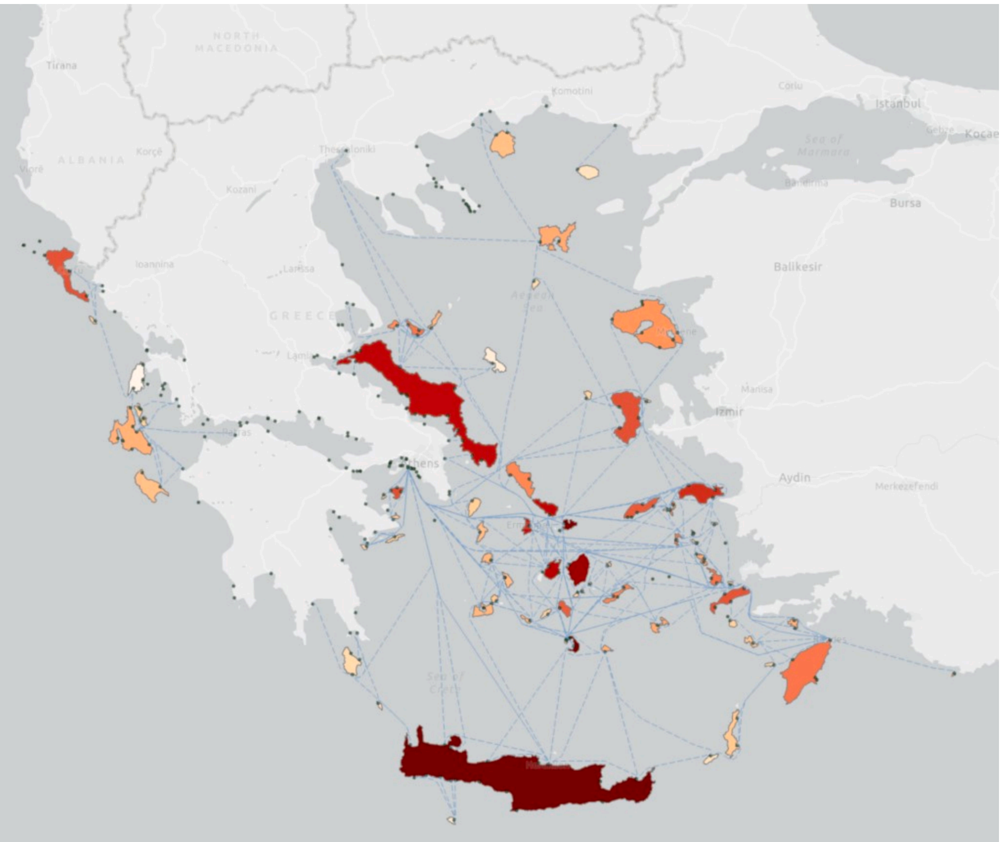

Fig. 3. Cartographic representation of normalized results of CI1 (Source: authors' own elaboration on data).

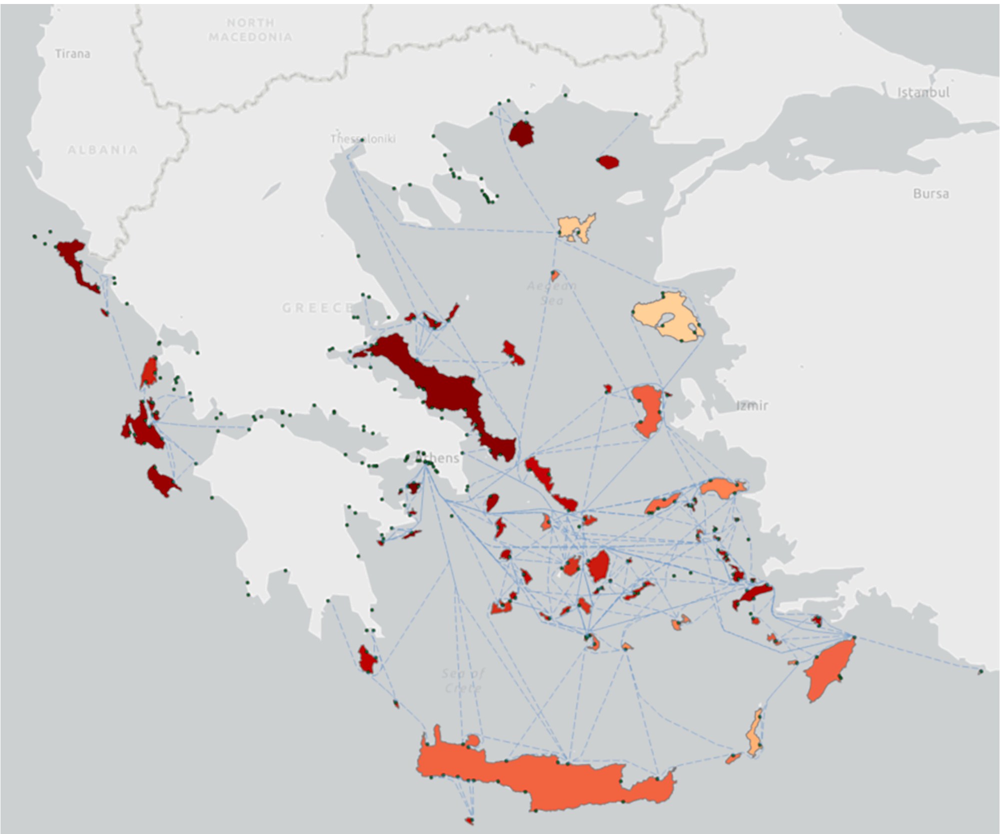

Fig. 4. Cartographic representation of normalized results of CI2 (Source: authors' own elaboration on data).

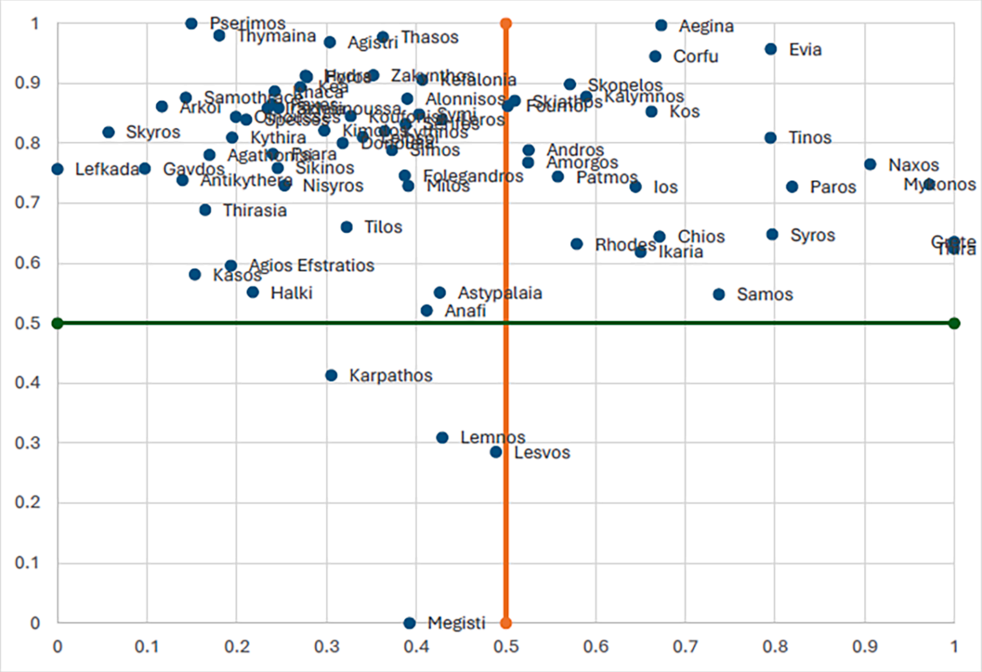

Fig. 5. Quadrant analysis and distribution of islands according to normalized CI1 and CI2 values (Source: authors' own elaboration).

concentrates the islands with strong accessibility but weaker connectivity, suggesting targeted interventions to enhance connectivity.

Twenty three islands fall within QC, including most of the Cyclades (i.e., Naxos, Mykonos, Thira, Paros, Syros, Tinos, Andros, Ios, Amorgos), large islands with significant populations and markets (i.e., Crete, Samos, Corfu, Kos, Chios, Kalymnos, Rhodes), and smaller islands that benefit from proximity to hubs or the mainland (i.e., Evia, Aegina, Skopelos, Ikaria, Patmos, Skiathos, Fournoi).

Most islands fall in QD. These islands enjoy reasonable accessibility but lag in connectivity. Tailored interventions should be guided by KPI-level analysis. For example, Gavdos, which depends heavily on Crete, may not feasibly increase its direct port connections but could improve connectivity by increasing the frequency of itineraries (from 212 port calls in 2018) to ensure daily service. Similarly, Lesvos, which in 2018 had only three direct connections with neighboring islands, could enhance connectivity by expanding both island and mainland links.

Only four islands are included in QA. Megisti stands out as the lowest performer in accessibility. Potential solutions could include deploying faster vessels to reduce travel time or restructuring the service network to shorten traveled distances, thereby improving both accessibility and connectivity simultaneously. No islands fall in QB.

5. Policy impact and future research

The proposed methodological approach for measuring connectivity and accessibility through SSS for passengers in Greece establishes a quantitative baseline that enables comparisons between pre- and post-Covid-19 conditions and identifying islands requiring prioritized policy interventions. Based on reliable and accessible data, and following multivariate analysis of potential KPIs, the selected indicators include the number of direct connections, port calls, operating vessels, average passenger capacity per itinerary, average travelled distances, average travel time, and average ticket price at the island level. These indicators reflect operational realities and are derived from data collected primarily at the port level.

The results of the CIs and KPIs reflect real operational conditions. Their cartographic representation, facilitated by the database's compatibility with GIS, enhances interpretation by integrating each island's geographic attributes (i.e., location, size, proximity to hubs, etc.). This approach allows policymakers to identify islands with weaker connectivity and accessibility and to tailor interventions based on KPI-specific insights.

While the current framework provides actionable insights, several limitations affect the validity of the results and policy relevance of the results. These limitations provide a clear rationale for integrating AI-driven methods into the framework for adaptive maritime governance.

'Direct connections' (SI1) quantify the number of the ports each island is connected to, including intra-island connections. However, this indicator does not account for functional dependencies between islands and between islands and the mainland. Integrating data on access to essential services (i.e., administrative, health, education, research, recreation, welfare) would identify connections essential for territorial cohesion. Classifying islands and ports based on their position within the settlement hierarchy would especially benefit smaller islands lacking essential services and dependent on higher-order centers. AI applications could automate dependency analysis, detect critical nodes, and dynamically update connectivity assessments.

'Port calls' (SI2) are currently derived from tickets issued by ship operators and submitted to HSKTHEEA, excluding itineraries without passenger traffic. This creates a gap in network assessment. AIS-derived data could capture all port movements, while timetable data could quantify discrepancies between scheduled and realized itineraries, including cancellations due to seasonal or severe winter weather. AI algorithms can process large-scale AIS datasets to enrich SI2, detect anomalies, and provide real-time updates to policymakers.

'Fleet size' (SI3), when combined with other network characteristics, assesses whether the number of operating vessels ensures reliable and frequent connectivity. The inclusion of substitute vessels for maintenance or repair enhances resilience but artificially increases SI3 performance. AI could model vessel deployment scenarios, optimizing fleet usage to balance service reliability and operational efficiency.

Data gaps currently undermine the reliability of 'average passenger capacity per itinerary' (SI4), limiting the evaluation of both capacity sufficiency and utilization rates. AI-driven imputation or predictive models could estimate missing capacity data using vessel characteristics and historical traffic patterns, enhancing KPI reliability.

'Average travelled distance' (SI5) accuracy is limited by the use of theoretical routes; actual AIS-derived trajectories would provide precise measurements. AI-based route processing and GIS integration could calculate realistic distance metrics and identify critical travel corridors.

'Average travel time' (SI6), presently calculated from scheduled departure times, does not reflect real conditions. AIS timestamps and vessel characteristics (i.e., speed categories, high-speed vs conventional) can provide more accurate travel time estimates. AI could automate integration of vessel attributes with route data to dynamically update travel time predictions.

'Average ticket price' (SI7) is estimated linearly based on distance, disregarding complex pricing dynamics influenced by service type, seasonality, or subsidy schemes. Enriching the database with real ticket prices and pricing criteria will strengthen SI7′s policy relevance. AI-driven pricing analysis could detect patterns, forecast fares, and model the impact of subsidy adjustments on accessibility.

These limitations are not simply avenues for future research; they are current constraints affecting the validity of this paper's findings. By framing KPI gaps as evidence for methodological improvement, the need for an AI-driven framework is explicitly justified. AI integration allows for dynamic, adaptive assessment of connectivity and accessibility, improving data quality, policy relevance, and resilience of maritime governance.

The methodological approach is not limited to passenger transportation. It can be expanded to freight SSS and international connections, enabling broader analysis of island connectivity. Moreover, the approach is part of a larger initiative to construct a composite territorial cohesion index, integrating dimensions such as (a) socio-economic factors like employment, education, health, demographics, tourism capacity and so on; (b) governance measuring impact of SSS policy measures and PSO routes; (c) spatial conflicts and synergies directly linked to MSP; and (d) environmental and technological performance considering emissions and vessel technology.

This integrated framework can benchmark island performance in relation to territorial cohesion, aligning SSS planning with broader policy domains such as MSP, sustainable transport, and regional development.

Currently, the framework sets a baseline using 2018 annual data. However, it is also applicable at shorter time intervals (quarterly or monthly), allowing the integration of seasonality, a key factor in SSS due to the sharp summer increase in tourism flows. Future research should apply the framework to subsequent years, enabling (a) tracking post-pandemic recovery and long-term shifts in connectivity and accessibility; (b) sensitivity analysis to examine KPI and CI response to changes in traffic, vessel deployment, and pricing policies; and (c) performance assessments where values exceeding 1 indicate significant improvements compared to baseline.

The framework is transferable beyond Greece to other coastal and island nations, at both national and cross-border scales. Its strength lies in the simplicity and harmonization of KPIs, many of which can be derived from internationally standardized data such as AIS. While some vessel-related data are only available through proprietary sources (i.e., Clarksons database), most KPIs remain broadly applicable. Challenges remain in collecting data on local passenger vessels without IMO identifiers and ticket prices, where national pricing mechanisms vary and are not always transparent. Despite these challenges, the framework's international adaptability makes it a valuable tool for advancing cooperation in SSS, MSP and territorial cohesion policy.

International cooperation is particularly crucial for enhancing the effectiveness of the proposed methodological framework, given that SSS networks often extend beyond national borders. Many Greek islands are linked to international ferry routes in the Adriatic, the Eastern Mediterranean, and the Aegean, making coordinated planning essential. Shared databases and harmonized KPIs, especially through the use of AIS data, can facilitate the monitoring and evaluation of cross-border maritime services. Cooperation through EU instruments such as the Trans-European Transport Network (TEN-T), Interreg programmes, and the European Green Deal can further ensure that island connectivity policies are consistent, sustainable, and supportive of territorial cohesion at both national and international levels. This would not only improve service efficiency but also promote resilience and inclusiveness in the wider European maritime transport system.

Future research can significantly enhance the framework through AI applications, addressing several key areas such as (a) data entry and transformation, including converting AIS into geospatial formats; (b) data imputation, filling missing vessel characteristics (i.e., length, width, passenger capacity) or estimating capacity from comparable vessels; (c) automated KPI and CI calculations, incorporating additional parameters (i.e., settlement network structure); (d) visualization, especially advanced cartographic outputs for policymakers; and (e) forecasting, where AI models use historical AIS and operational data to predict future SSS patterns, set performance targets and test scenarios. This would expand the framework from a monitoring and evaluation tool to a forward-looking planning instrument, supporting policy decisions under various projected scenarios.

Beyond technical automation, the integration of AI applications and tools can provide significant policy-level benefits. AI-driven analyses can generate real-time insights into the reliability and sustainability of island connections, optimize the allocation of subsidies for PSO routes, and assess the potential impacts of different network scenarios on passenger flows and emissions. In the context of climate change and the green transition, AI can model how alternative vessel technologies or changes in service frequency influence both environmental outcomes and accessibility. Moreover, AI-enabled forecasting can support contingency planning during crises, such as pandemics or extreme weather events, by simulating demand shifts and capacity needs. To ensure transparency and trust, future research should also consider the governance of AI applications, including data ethics, privacy, and accountability in decision-making processes.

6. Conclusions

Short sea shipping is a critical sector for achieving territorial cohesion among islands and between islands and the mainland, while also intersecting with broader governance, economic, and MSP objectives. This case study proposes a methodological approach for measuring connectivity and accessibility in the Greek passenger SSS network, using a set of carefully selected KPIs. These included the number of direct connections, port calls, fleet size, average passenger capacity per itinerary, average travelled distance, average travel time and average ticket price. A dedicated database (EVDAD) integrating historical data on the Greek SSS, with partial automation for data entry, was employed. KPIs were normalized using the Min-Max method and aggregated through a weighted arithmetic mean into CIs designed to conceptually reflect, quantify, and measure connectivity and accessibility. These CIs enabled benchmarking and ranking of islands and were visualized to support decision- and policy-making processes in SSS planning as well as governance-related policies such as MSP and territorial cohesion strategies.

The KPI-based case study revealed critical limitations of traditional methods, including incomplete coverage, reliance on estimated values, and simplified assumptions that may distort real operational conditions. These limitations demonstrate that standard KPI frameworks, while useful for descriptive benchmarking, are insufficient to fully capture the complexity and dynamic nature of SSS networks. Explicit acknowledgment of these methodological constraints ensures transparency and scientific rigor and provides the rationale for the development of more adaptive, intelligent approaches.

To address these challenges, the study proposes a conceptual AI-driven framework as its primary intellectual contribution. Integrating AI tools enable dynamic data imputation, automated KPI and CI calculation, advanced visualization, anomaly detection, and scenario-based forecasting. This approach transforms the framework from a descriptive benchmarking tool into a forward-looking instrument for adaptive maritime governance, supporting evidence-based policy interventions under variable operational, environmental, and socio-economic conditions.

The proposed methodological approach is transferable to other dimensions of SSS, including freight and vehicle transportation and international connections. Given the simplicity and international harmonizations of the KPIs and CIs framework, this methodology is applicable beyond Greece at both national and international scales, especially in coastal and insular contexts served by SSS. It can also foster international cooperation by providing a harmonized, data-driven framework for prioritizing policy interventions. By combining empirical insights from the KPI case study with AI-enhanced methods, the framework bridges the gap between traditional performance measurement and adaptive, policy-relevant governance.

This study demonstrates that while KPI-based analysis provides valuable baseline, their limitations necessitate the conceptual AI framework proposed in this paper. Integrating AI not only improves data quality and policy relevance but also enhances the resilience, adaptability, and sustainability of SSS planning. Future research should focus on operationalizing this AI-driven framework, expanding its scope, and incorporating additional socio-economic, governance, environmental, and technological indicators to support comprehensive MSP and territorial cohesion strategies.

CRediT authorship contribution statement

Vasiliki-Maria Perra: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Maria Boile:** Writing – review & editing, Validation, Supervision, Conceptualization.

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.trip.2025.101819.

Data availability

The data that has been used is confidential.

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