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Research article

Strategic analysis of hub port competitiveness in the Mediterranean and Northern Europe: a focus on sustainability and efficiency

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Abstract: The evolution of mega-ships and maritime alliances, in tandem with global changes, has intensified hub port competitiveness, increasing the need for innovation and adaptation, with a focus on sustainability. This study analyzed the competitiveness of the Mediterranean maritime hub port with Northern European ports. It provided a comprehensive analysis of the competitiveness of ten leading international hub ports in the Mediterranean and Northern Europe. Using the Hybrid F-AHP TOPSIS method, this research first identified and assigned weights to 10 criteria across five categories of port competitiveness from a shipping liner perspective in the Mediterranean and Northern Europe. It then ranked those ten leading ports based on the weighted criteria. The results showed that handling cost, operational efficiency, and infrastructure were the main factors for defining a competitive hub port, with growing emphasis on sustainability considerations. The results also highlight that Tangier Med, Algeciras, and Port Said were the leading ports in the region, excelling in technical efficiency and maritime costs compared to Northern European ports. The analysis further provided a holistic overview of competitiveness in the region, identifying the strengths and opportunities of each port based on 5 aspects with a special focus on the hub ports of the Southern Mediterranean. This research offers valuable insights for maritime shippers and port authorities in understanding hub port performance and competitiveness in a sustainable context.

Keywords: competitiveness port; criteria of competitiveness; hub ports; logistics port; sustainability of port; MCDM analysis

1. Introduction

The development of mega-ships and the strategic alliance of major shipping lines have transformed the organization of port call patterns by creating several strategic mega-hubs. These trends have led to the exclusion of historical ports, transforming them from global hubs into regional ones, particularly in areas of high maritime competition [1]. In this context, maritime transport on East-West routes has undergone significant developments and changes influenced by various factors, including global economic shifts, the COVID-19 pandemic, and changes in shipping industry strategies [2]. The Mediterranean has emerged as a critical juncture in global maritime trade, thanks to new strategic port hubs along the Suez Canal and Gibraltar routes, such as Gioia Tauro, Piraeus, and Tangier Med [3]. This has not only strengthened the region's strategic importance but also intensified competition for cargo volumes between the northern and southern shores of the Mediterranean and the well-equipped ports of Northern Europe [4].

In this dynamic context, hub ports are facing increased uncertainty and volatility, requiring agile management and planning strategies, infrastructure, and flexible logistics services. Pressure on profit margins is driving ports to innovate and differentiate, accentuating the trend towards market consolidation and strategic partnerships, by enhancing their role in supply chain optimization to stay competitive, as traffic volume alone is no longer a sufficient indicator of success. Consequently, shipping lines are adjusting their port selections based on different evolving factors like efficiency, pricing strategies, and competitive advantages. Moreover, the adoption of environmental strategies aimed at reducing CO2 emissions will potentially reconfigure routes and port maps [5–7].

The existing literature on port competitiveness criteria reveals a wide range of factors influencing this competitiveness, such as location, connectivity, and port management. However, a significant part of these studies focuses on the competition between neighboring ports and often confines to the European and Asian contexts, thus overlooking global maritime network lines. This situation uncovers a crucial gap: the absence of a global analysis of port competitiveness that considers the integration of ports into international maritime networks. This lack of a global perspective neglects essential dynamics of global maritime trade, limiting our understanding of the impact of hub ports on regional and global commerce [8].

In the face of this identified gap, the issue of our research was to transcend the analysis of port competitiveness on the East-West axis by integrating both the North range and the South range, as well as the North European ports, as recommended by the Portopia initiative or the World Bank. This balanced traffic between the North and South ranges across the Mediterranean coasts, taking into account strategic considerations and increasing competition. This approach aimed to broaden our understanding of port competitiveness beyond the mere comparison between neighboring ports, by embracing a global perspective that took into account the global supply chain vision [9]. This holistic approach saught to improve our understanding of port competitiveness by considering the sustainability of ports as essential elements of global maritime networks.

Our research project examined the major hub ports located along the critical East-West shipping routes, comparing both ports in developed countries (Europe) and ports in the southern range (North Africa). The study aimed to highlight the differences and similarities between the ports, with a particular focus on the latent development opportunities in North African ports. Through this comparative analysis, our research aimed to provide important insights into:

- Addressing the criteria that define the competitiveness of the main hub ports from a liner perspective and their relative weight.
- Identifying the most important hub ports through a competitive analysis framework and ranking the ports evaluated.
- Outlining the strengths and potential areas for improvement and identifying the most attractive ports for liner shipping.
- Recommending policy reforms and strategic investments that could enhance the role of North African ports in the global supply chain, thereby increasing their competitiveness and integration into global value chains.

Through this analysis, our research aims to make a significant contribution to the understanding of the dynamics of hub port competitiveness, particularly in North Africa. The results of these studies will be used to guide shipping lines in their port selection decisions, and possibly to capitalize on success stories to develop hub ports that wish to integrate into a similar approach.

Our study uses a mixed approach, combining quantitative and qualitative analysis to assess the competitiveness of ten leading international hub ports in the Mediterranean and Northern Europe. First, we conducted a comprehensive literature review to identify the most frequently cited selection criteria for port hubs. These criteria include various factors related to port operations, costs, service, sustainability, and macroeconomics. We collected quantitative data such as maritime traffic volumes, port capacity, and infrastructure quality to provide a solid empirical basis for comparison. In parallel, we conducted qualitative research through expert interviews. We interviewed maritime industry professionals using a structured questionnaire designed based on the identified selection criteria. The data collected was then analyzed using a hybrid multi-criteria method combining the Fuzzy Analytical Hierarchy Process (FAHP) for qualitative data and the Technique of Order of Preference by Similarity to the Ideal Solution (TOPSIS) for quantitative data. FAHP is used to assign weights to each criterion based on expert opinion. These weights are then applied to the quantitative data using TOPSIS to assess and rank the competitiveness of the ports studied. This innovative analytical framework allows a nuanced comparison of port competitiveness in different contexts, providing insights into the strategic advantages and challenges of each port.

Our manuscript is organized as follows: After defining our scope, we present the literature review, which examines existing research on port competitiveness, particularly in well-developed maritime economies, noting a lack of focus on developing regions. We then describe our research methodology, a mix of data collection and analysis techniques. This is followed by the results of our case study, presenting the findings on the hub ports within a defined scope. Finally, the manuscript concludes with a discussion of the implications of our findings for port competitiveness and strategic recommendations for maritime development, with particular emphasis on the potential within the North African ports.

Through this investigation, our research aims to provide significant insights and contribute to the discourse on the dynamics of hub port competitiveness, with the ultimate goal of enhancing sustainable maritime development in the Mediterranean context.

2. Scope definition

Given the growing influence of the Southern Mediterranean ports on the international scene, initiatives such as Portopia suggest that Southern ports should be included in the statistical analysis of

Mediterranean and European ports [3]. This recommendation is in line with the World Bank, which has already highlighted a significant imbalance in the distribution of Mediterranean maritime traffic, with ports on the EU's northern shore accounting for over 70% of activity. This shows the need for action to rebalance maritime growth between the northern and southern shores [1]. Moreover, Mediterranean ports are in competition with ports in Northern Europe and are influenced by initiatives such as the emerging Arctic route and the Belt and Road Initiative. In order to regain their pre-eminence in the international maritime arena, these ports need to develop and implement an integrated strengthening strategy that takes into account both the technical and strategic aspects of their activity [11].

The Mediterranean, located at the crossroads of the maritime routes linking Europe, Africa, and Asia, handles 40% of the world's container traffic, with traffic increasing by 160% since 2002 and set to reach 60,000 TEU by 2022. The Mediterranean ports are analyzed in conjunction with those of Northern Europe, which are major players in the Northern Range and key entry points for trade flows to and from Europe [12].

This paper examines the main hub ports within the Mediterranean and Northern Europe, focusing on their competitive dynamics. The top 10 ports selected are Rotterdam, Antwerp, Hamburg, and Bremerhaven in Northern Europe; Valencia, Piraeus, Algeciras, and Gioia Tauro in the Northern Range; and Tangier Med and Port Said in the southern range. Barcelona is excluded from this study due to its gateway vocation.

Table 1. List of top 10 ports in Mediterranean and North African ports [5,13].

	Container Traffic 2021	Growth 2020–2021	Growth 2007–2021	Transshipment Incidence
Rotterdam	13294	7.80%	41.80%	33%
Antwerp	11970	-0.10%	47%	40%
Hamburg	8578	2.20%	-11%	40%
Valencia	5413	3.40%	84%	50%
Piraeus	5202	-2.20%	287%	82%
Bremerhaven	4767	5.20%	2.60%	42%
Algeciras	5108	-6.10%	40.30%	95%
Barcelona*	3531	19.40%	35.30%	18%
Gioia Tauro	3320	-1.50%	-8.70%	98%
Tangier Med	7 173	24%	100%	98%
Port Said	4760	11%	42%	95%

As shown in Table 1, the ports of Northern Europe and the Mediterranean show contrasting dynamics in terms of container traffic and transshipment rates. Between 2020 and 2021, Rotterdam saw a significant increase of 7.8%, while Antwerp declined by 0.1% and Hamburg grew by 2.2%. These ports have substantial transshipment rates, varying between 40% and 42%. Since 2007, these ports have recorded significant growth, with Rotterdam and Antwerp standing out with increases of over 40%. However, Hamburg has seen a decline of 11%, reflecting the challenges faced by some historic ports in the face of the reconfiguration of shipping lanes and carrier alliances.

For the Mediterranean ports, the variation in traffic shows dynamism, with Tangier Med recording a 24% increase, while Valencia and Piraeus saw moderate increases of 3.4% and a 2.2% fall, respectively. Transshipment rates in these ports are particularly high, with Piraeus at 82%, Algeciras at 95%, and Tangier Med and Gioia Tauro reaching 98%. Mediterranean ports, including Valencia, Piraeus, Algeciras, Gioia Tauro, Tangier Med, and Port Said, have shown impressive growth momentum, with Piraeus and Tangier Med leading with the highest. These figures reveal the strong dependence of Mediterranean ports on transshipment and the variability in container traffic growth, in contrast to the northern ports which are maintaining stable growth with high transshipment rates but generally lower than those observed in Mediterranean ports.

3. Literature review

Since the 1980s, research on port competitiveness has evolved from focusing on basic factors like sailing distance or cost [14] to more complex considerations like waiting time and service capacity [15], call frequency and port congestion [16], and port costs and cargo damage experience [17,18]. Later studies have included loading/unloading capacity [19], highlighting the importance of location and transport efficiency [20]. From the early 2000s, port efficiency became a key indicator [21–27], with a growing demand for diverse services with an emphasis on value-added logistics services [22] and logistics zones in boosting port competitiveness [23]. Despite this broad focus, most studies concentrate on European and Asian ports, with less attention to the Americas and minimal attention to Africa and Oceania [9].

Competitiveness studies on Asian ports have analyzed various criteria, ranging from cost, management, and location to service quality and operational efficiency. LIRN's analysis of Taiwanese ports focused on cost, management, and location using AHP analysis [28]. Ha's assessment service quality in 15 major container ports worldwide identified location, lead times, facilities, cost, and management as key factors [29]. Song and Yeo applied the AHP method to evaluate the competitiveness of Chinese container ports, including Hong Kong, focusing on container volume, location, facilities, and services [30]. Chang et al.'s research from shipping lines' perspectives confirmed that the physical/operational abilities of ports are the most important factor from a shipping liner's perspective [31]. Yi and Shu assessed the competitiveness of Northeast Asia's major ports—Busan, Tokyo, and Kaohsiung—using 20 criteria across five dimensions: political-economic environment, operations, cost, infrastructure, and incentives [1]. Dang and Yeo identified key factors influencing the competitiveness of Chinese and Korean ports, highlighting port service, hinterland conditions, availability, logistics costs, logistics hubs, and connectivity as crucial in the region [32]. Kavirathna et al. evaluated the performance of competing port hubs around the Bay of Bengal, emphasizing factors such as cost, lead-time, geography, and operations for hub-and-spoke and relay networks [33]. Port logistics is recognized as a top-ten industrial sector, contributing significantly to regional port competitiveness and economic development [34]. Kavirathna et al. assessed the competitiveness of the port of Colombo, focusing on quantitative criteria like port charges, detour costs, connection costs, and non-quantitative indicators such as location, operations, and human resources [35]. Another article concludes that port charges and the availability of a wide range of port services are the most significant factors influencing the port choice of shipping lines. This finding highlights the importance of cost and service diversity in port operations for the major shipping lines operating in Singapore and Malaysia [36].

Several European studies have explored port attractiveness. From a shipping line perspective, NG examined the attractiveness of container transshipment ports in Northern Europe. The results highlighted that cost is not enough to explain the attractiveness of a port. Other factors, such as time efficiency, geographical location and quality of service are to be taken into consideration [37]. Research emphasizes the importance of hinterland connections, market size, feeder connectivity, environmental concerns, and traffic volume in choosing ports and terminals, highlighting efficiency, reliability, and cost as crucial criteria [38]. Saeed's statistical analysis in Europe points to loading/unloading rates, handling charges, and service quality as key factors for container terminal selection, with personal contacts or shipping line investments given less emphasis [39]. Tsakiridis et al. evaluated the performance of Irish and Spanish North Atlantic ports by examining efficiency changes during the period 2000–2015. Technical efficiency scores were derived using stochastic frontier analysis [40]. Another study on prominent ports in Asia and Europe shows that the adoption of eco-friendly policies, particularly in maritime traffic activities, plays an important role in attracting port clients [41]. In the Mediterranean, competitiveness studies using DEA and Fuzzy AHP analysis identified market share, location, accessibility, infrastructure, cost, and safety as key competitiveness factors [42,43].

From the point of view of the main shipping lines serving ports in Africa, efficiency, ship visit frequency, infrastructure, and rapid response are highlighted as key criteria for Nigerian ports from the perspective of major shipping lines [44]. The World Bank and studies like Van Dyck emphasize the need for enhanced efficiency, performance, stable political environments, and adequate infrastructure for West African hub ports, with Abidjan ranked as the most competitive [45,46]. Factors such as infrastructure, port draught, political stability, market size, and international networks are crucial for port selection in Africa [47].

The evolution of ports in the global economy highlights their growing role beyond transit points to strategic logistics centers that integrate the development of Free Trade Areas (FTAs). This transformation is driven by the need to increase competitiveness and sustainability through regionalization, hinterland improvement, and the adoption of sustainable logistics practices. As a result, ports are no longer simply managing the flow of goods, but are becoming key hubs of economic activity, offering value-added services, and strengthening their position in the global supply chain network [48–50].

A thorough review of the literature on port competitiveness criteria reveals a wide variety of criteria that vary by region and perspective, including location, connectivity, cost, market size, port performance, quality of service, value added, port management, port-related logistics, and environmental aspects. Previous studies in maritime economics have mainly focused on the competitiveness of neighboring ports, often neglecting the context of global liner networks. Additionally, it concerns the European and Asian context. This gap overlooks a crucial part of the dynamics of global maritime trade in relation to analyzing competitiveness on a global scale. Our study aimed to fill this gap by focusing on the hub ports in maritime axes, from different countries, assessing their role in wider shipping networks and their impact on a regional and global scale, which is essential for the development of more effective maritime trade strategies and policies.

Table 2. Selection criteria for port hubs in previous studies.

Number	Criteria	Reference
1	Location	[33,37]
2	Market size	[33,38,47]
3	Maritime connectivity	[30,31,33,38,44,47]
4	Port facilities (infrastructure and superstructure)	[30,33,39,44,46,47]
5	Port efficiency	[38,40]
6	Quality of port services	[29,33,37,39,47]
7	Added value	[39,48,49]
8	Logistics activity	[32,34,48,51]
9	Port charges	[30,33,39,44,46,47]
10	Handling charges	[39,43]
11	Port management	[28,29]
12	Environmental aspects	[38,41]
13	Port capacity	[31]

Table 2 shows the 13 factors identified as having a direct or indirect impact on port competitiveness. These factors are port hub location, market size, connectivity, available facilities, port services, cost, port management, port capacity, and sustainability.

The analysis did not consider port location and management. The exclusion of location is justified by the distinct geographical characteristics of each port and its mainline proximity, which would not substantially alter the findings. Management was omitted because of its challenging quantification.

4. Classification and definition of selected criteria for the analysis of port competitiveness

The literature review confirmed that port competitiveness analysis is a complex subject that requires several criteria to evaluate its performance and attractiveness effectively. It highlights that the traditional definition of a port hub's competitiveness mainly concentrates on its technical, commercial, and financial characteristics, with the recent addition of sustainability indicators. For each criterion identified, we use one or more performance indicators, providing a precise and comprehensive measure of the port's competitiveness. The criteria identified have been classified under several aspects responding to the challenges of today's port's competitiveness as shown in Figure 1. These criteria will be defined and presented individually in the following sections for a more in-depth understanding.

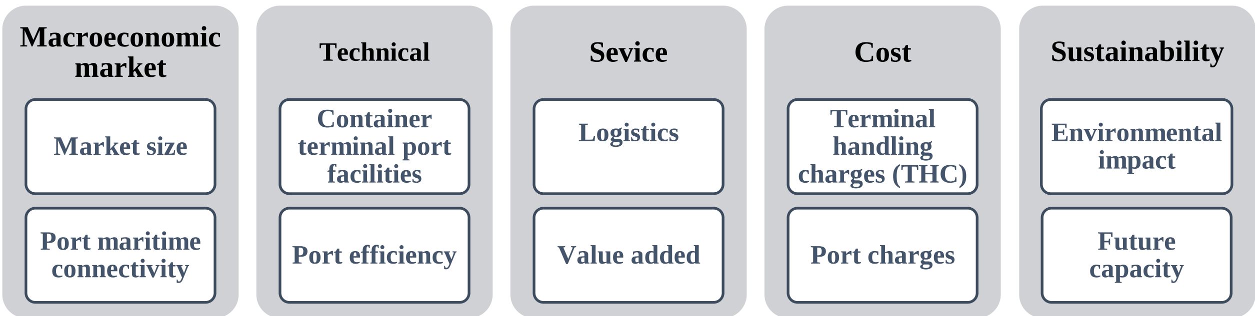

Figure 1. Classification of selected criteria of port competitiveness analysis.

4.1. Macroeconomic market

The macroeconomic market aspect refers to large-scale criteria at the national or international level, where the port operates. It includes indicators relating to the market size served by the port, and its openness to external markets represented by connectivity.

Market size represents the level of market capture and many indicators have been produced by monitoring organizations. Market size can be assessed by various indicators provided, such as maritime traffic, which measures the level of throughput of goods served by ports, as well as the number of ship types that reach the port [52].

Port maritime connectivity refers to the ability to integrate into maritime logistics chains seamlessly with container services (liner shipping) and other scheduled services to other destinations.

4.2. Technical category

The technical category of a port encompasses all elements related to its infrastructure and superstructure, as well as the efficiency of the operations carried out there. It encompasses the essential criteria for determining a port's quality and functionality.

Container terminal port facilities include the physical infrastructure like quays, terminals, and warehouses, and the superstructure comprising operational equipment such as cranes. These elements must be well-designed, maintained, and safety-compliant to enhance operational speed and resource use. The main indicator for assessing port facilities is the port infrastructure quality index [30,36,37,47].

Port efficiency depends on the suitability of their facilities, measured by ship turnaround, dwell, and waiting times. Interdependent maritime, terminal, and hinterland operations require effective coordination to minimize inefficiencies and optimize port functioning. Efficient container handling is key, especially in ports with limited expansion capacity [53,54].

4.3. Cost category

Cost is a principal factor in port competitiveness, as it contributes to sustainable competitive advantage. Cost is one of the most important criteria for companies and ship owners when choosing a port [30,33,39,44,46,47]. Costs related to the port can be grouped into two main categories:

Terminal handling charges (THC) represent the fees collected by terminal operators from shipping lines.

Port charges depend on the suitability of their facilities, measured by criteria such as ship turnaround time, dwell time, and waiting time in port. Due to difficulties in finding comparable data across ports, these charges were excluded from our analysis, highlighting the need for reliable and comparable data. Instead, we used the demurrage and detention (D&D) indicator, which estimates costs for containers stored beyond free days, offering a general view of storage-related expenses in a terminal [55].

4.4. Service category

Port services refer to the services offered in and around a seaport to support shipping and cargo handling operations.

Logistics performance assesses the ability to effectively manage its supply chain, including infrastructure quality and ease of international shipping, logistics service competence, shipment tracking, and the frequency of delivery to the consignees. Measured by the World Bank's Logistics Performance Index, it provides a global overview of a country's logistics efficiency in world trade [56].

Port value added encompasses freight-enhancing activities around terminals. This includes processing (packaging and assembly), efficient distribution, free trade zones for less taxed activities, and container depots for storage and distribution. Added value is an indicator that is increasingly integrated into port activity reports.

4.5. Sustainable aspect

Sustainability is becoming a crucial factor in the competitiveness of port hubs, highlighting environmental, social, and economic aspects. The focus in achieving sustainability is on reducing environmental impacts, improving the quality of life, and addressing socio-economic priorities such as employment and education. This encompasses:

Environmental impact is increasingly important in port selection, and standardizing assessment indicators remains challenging, with CO2 emissions being a commonly reported metric [57].

Future capacity: UNCTAD highlights the need for capacity building to ensure economic sustainability and global competitiveness, involving infrastructure enhancement, technology adoption, personnel training, and strategic partnerships, with forecast capacity as a key indicator. Social aspects were not analyzed due to their subjective nature and the challenges in direct competitive comparison.

5. Research methodology and data

The literature proposes various methodologies for analyzing port competitiveness. We can find productivity, efficiency, performance, and port selection analysis. Different research methods are used for the selection of ports, such as performance analysis models [58–60], economic and managerial approaches like SWOT analyses or benchmarking models, mathematical programming models [61], multi-criteria decision-making models [28,30,62], fuzzy multi-criteria decision-making models [63], as well as hybrid models [64]. A systematic review from 1993 to 2015 shows hybrid MCDM methods as the most prevalent in the port sector, followed by AHP and Fuzzy-AHP, with techniques like TOPSIS and ANP also widely used [9,65–68].

Decision-making (MCDM) methods, particularly the combination of Fuzzy Analytic Hierarchy Process (FAHP) and TOPSIS, are widely utilized. This approach is ideal for our study as it provides a comprehensive and reliable assessment of port competitiveness by managing subjectivity and uncertainty, focusing on key criteria such as connectivity, quality of service, operational efficiency, and environmental performance [31,69–71]. The rationale of the method is presented in Figure 2.

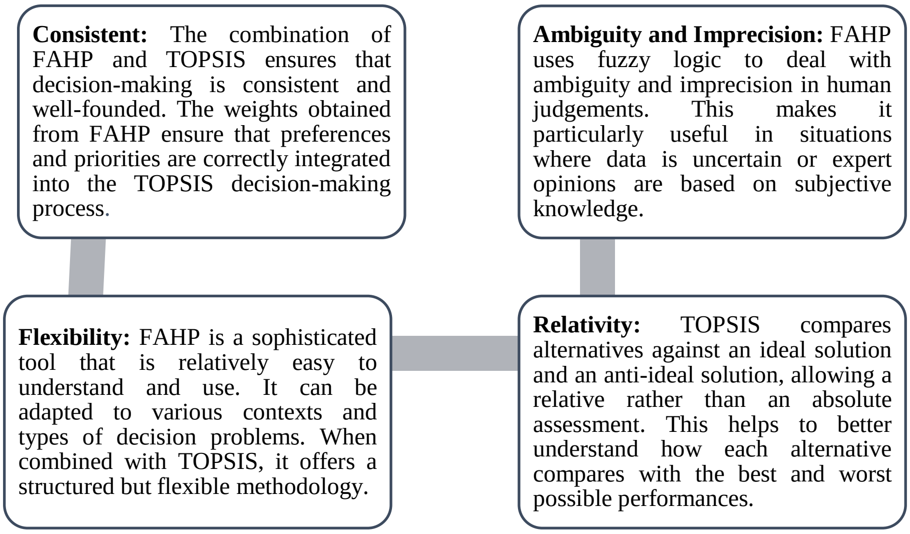

Figure 2. Rational of FAHP-TOPSIS methodology.

5.1. Constructing a decision-making hierarchy

The Analytic Hierarchical Process (AHP) involves decomposing a decision problem into a structured hierarchy. The primary objective at the first level of the hierarchy is to choose hub ports in the Mediterranean and Northern European ports. The second level of the hierarchy categorizes the criteria, such as the "technical" category, that contains specific criteria. The third level corresponds to the criteria to which the competitiveness of ports is attributed, as identified in the literature. In the case of the "technical" category, the criteria include "facilities" and "efficiency". Finally, at the bottom of the hierarchy in Figure 3, the main container hub ports included in our analysis are listed.

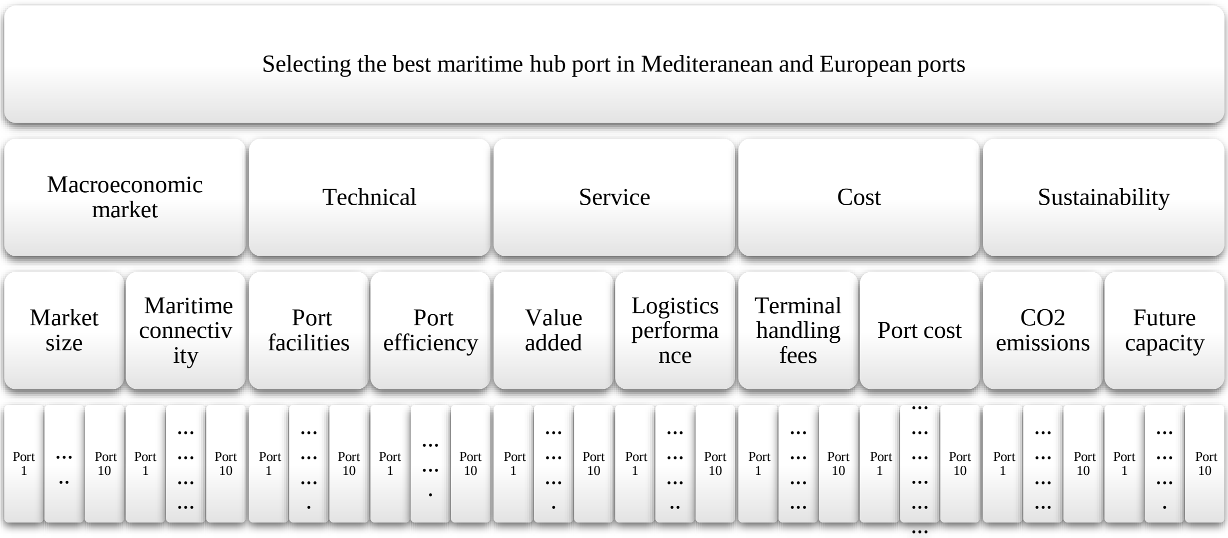

Figure 3. Hierarchy of the criteria-selecting problem.

5.2. Data collection

Quantitative data: The quantitative data collection method involves the acquisition of accurate data and statistics, including maritime traffic volumes, port capacities, and the volume of infrastructure investment, as well as other measurements of criteria selected in part 3.2, by exploiting official documents from international organizations (such as the World Bank and UNCTAD) to collect reliable and comparable data. Furthermore, it involves the examination of official websites of the selected port (annual operational, financial, and environmental reports). This approach provides a robust empirical foundation for making objective comparisons between the ports studied.

Qualitative interviews: The aim of this phase of the research is to use expert judgement to determine the relative importance of the various criteria that influence shippers' choice of hub ports in Mediterranean and European hub ports. To achieve this, a group of experts is asked to make pairwise comparisons between the identified criteria based on the Saaty scale. This scale ranges from 1, indicating equal importance between two criteria, to 9, indicating that one criterion is extremely more important than the other. It allows for precise quantification of expert preferences and perceptions. The results of these pairwise comparisons are then analyzed to generate relative weights for each criterion.

5.3. Data analysis with FAHP

The FAHP methodology, applied to the responses to Saaty's questionnaire, uses fuzzy numbers, typically triangular, to assess the relative importance of criteria and categories in the analysis of port competitiveness. Based on Zadeh's theory of fuzzy sets, which allows imprecision to be managed by assigning each element a degree of membership between 0 and 1, this approach incorporates linguistic variables to describe complex concepts [72, 73]. Triangular fuzzy numbers, defined by a triplet of real numbers, facilitate this description. Using Chang's method, relative weights are calculated.

- Triangular Fuzzy Number and Arithmetic Operations

In fuzzy set theory, linguistic variables are expressed in words or natural sentences to describe complex or vaguely defined concepts. These variables are often represented by triangular fuzzy numbers, defined by a triplet of real numbers (l, m, u), representing the minimum, most probable, and maximum values, respectively. The membership function of these numbers, $\mu(x)$, assigns each element x a real value within the [0, 1] interval. This assignment is based on a specific formula that varies depending on x in the interval [0, 1] to l, m, and u [71,73]:

$$\mu(x) = \begin{cases} 0 \ , & x < l \\ \dfrac{x-l}{m-l} \ , & l \leq x < m \\ \dfrac{u-x}{u-m} \ , & m \leq x < u \\ 0 & (x \geq u) \end{cases} \tag{1}$$

Chen introduced a simplified arithmetic for these numbers, based on simple additions or subtractions between the values of their parameters (2), (3), (4), and (5) below [2].

$$\tilde{a}_1 + \tilde{a}_2 = (\mathrm{l}_1 + \mathrm{l}_2, \mathrm{m}_1 + \mathrm{m}_2, \mathrm{u}_1 + \mathrm{u}_2) \tag{2}$$

$$\tilde{a}_1 - \tilde{a}_2 = (\mathrm{l}_1 - \mathrm{u}_2, \mathrm{m}_1 - \mathrm{m}_2, \mathrm{u}_1 + \mathrm{l}_2) \tag{3}$$

$$\tilde{a}_1 \times \tilde{a}_2 = (\,l_1 \times u_1,\, m_1 * m_2,\, l_2 * u_2) \tag{4}$$

$$\tilde{a}_1 / \tilde{a}_2 = (\frac{l_1}{u_2}, \frac{m_1}{m_2}, \frac{l_2}{u_1}) \tag{5}$$

The distance between two fuzzy numbers can be measured using the Euclidean distance, considering the differences between their membership functions [2].

$$d(A, B) = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\mu_A(x_i) - \mu_B(x_i))^2} \tag{6}$$

Where μ_{AI} and μ_{Bi} are the membership degrees of the elements of A and B, respectively.
In the case of triangular fuzzy numbers, the variable is represented by a triplet ã (l, m, u). Chen proposed a method to calculate the distance between two triangular fuzzy numbers, defined by Eq 8. Thus, if $\tilde{a}_1\ (l_1, m_1, u_1)$ and $\tilde{a}_2\ (l_2, m_2, u_2)$ are two triangular fuzzy numbers, their distance can be calculated as follows.

$$d(\tilde{a}_1, \tilde{a}_2) = \sqrt{\frac{1}{3}\ ((l_1 - l_2)^2\ + (m_1 - m_2)^2 + (u_1 - u_2)^2} \tag{7}$$

The following formulas allow for the calculation of the aggregate matrix values from a set of p triangular fuzzy matrices:

$$l_{ij} = \min_{k\epsilon(1 \ldots P)} (l_{ijk}) \tag{8}$$

$$m_{ij} = \left[\prod_{k=1}^{P} m_{ijk}\right]^{1/P} \tag{9}$$

$$u_{ij} = \max_{k\epsilon(1 \ldots P)} (u_{ijk}) \tag{10}$$

- **FAHP Steps**

The steps involved in implementing the FAHP method according to [74] are presented below:

1. Define the problem and identify the criteria: The first step is to clearly define the problem to be solved and identify the relevant criteria for evaluating the alternatives. The criteria should be arranged in a hierarchy of levels, so that the higher criteria are more general and the lower criteria are more specific.

2. Construct comparison matrices: Using triangular fuzzy numbers, by means of pairwise comparisons, the fuzzy evaluation matrix $A = (a_{ij})n \times n$ is constructed.

Then, comparison matrices are constructed for each level of the hierarchy. In each comparison matrix, the criteria are compared two by two using fuzzy numbers. The fuzzy values represent the uncertainty or imprecision of the evaluations.

Consider the following fuzzy comparison matrix:

$$\tilde{A} = \begin{pmatrix} (1,1,1) & \cdots & (l_{1n}, m_{n1}, u_{n1}) \\ \vdots & \ddots & \vdots \\ (l_{n1}, m_{n1}, u_{n1}) & \cdots & (1,1,1) \end{pmatrix}$$

with $\tilde{a}_{ij} = \tilde{a}_{ji}^{-1}$ and $\tilde{a}_{ji}^{-1} = (\frac{1}{u_{ij}}, \frac{1}{m_{ij}}, \frac{1}{l_{ij}})$

3. Calculate the value of the fuzzy synthetic range:

$$RS_i = \sum_{j=1}^{n} \tilde{a}_{ij} = (\sum_{j=1}^{n} l_{ij}, \sum_{j=1}^{n} m_{ij}, \sum_{j=1}^{n} u_{ij}) \text{ with } (i = 1\ldots, n) \tag{11}$$

$$S_i = \sum_{j=1}^{n} a_{ij} * \left[\sum_{i=1}^{n} \sum_{j=1}^{n} a_{ij} \right]^{-1} \tag{12}$$

$$\left[\sum_{i=1}^{n} \sum_{j=1}^{n} a_{ij} \right]^{-1} = \left(\frac{1}{\sum_{i=1}^{n} u_{ij}}, \frac{1}{\sum_{i=1}^{n} m_{ij}}, \frac{1}{\sum_{i=1}^{n} l_{ij}} \right) \tag{13}$$

4. Calculate the degree of possibility of $M_1 > M_2$ using the following formula:

$$V(M_1 \geq M_2) = sup \{Min\ \mu_{M1}(x), \mu_{M2}(y)) : x > y\} \tag{14}$$

5. Calculate the degree of possibility of $\hat{s}i \geq \hat{s}j$ as proposed by Chang (1996) [69,74]:

$$V(\hat{s}i \geq \hat{s}j) = \mu(d) = \begin{cases} 1 & , m_i > m_j \\ \frac{ui-lj}{(ui-mi)+(mj-lj)}, & lj \leq ui \quad i,j = 1,\ldots,n \text{ and } j \neq i \\ 0, & otherwise \end{cases} \tag{15}$$

Where d is the ordinate of the highest intersection between μ_{M1} et μ_{M2}.

6. Calculate the degree of possibility for each $\hat{s}i$ with respect to the other fuzzy numbers (V ($\hat{s}i \geq \hat{s}j$) /j = 1,…..n , j≠i): The degree of possibility for a convex fuzzy number to be greater than k convex fuzzy numbers M_i (i = 1, 2, ..., k) can be defined by Eq 17:

$$\begin{aligned} V(M > M_1, M_2, \ldots, M_K) &= V[(M > M_1) \text{ and } (M > M_2) \ \ldots \text{ and } (M > M_K)] \\ &= \min [V(M > M_i), \quad i = 1, 2, \ldots, k] \end{aligned} \tag{16}$$

Consider that

$$d(A_i) = min[V(S_i > S_k), for\ k = 1,2, \ldots .n] \tag{17}$$

Then, for n criteria, the weight vector is given by:

$$W' = \left(d'(A_1), d'(A_2), \ldots, d'(A_n) \right)^T, \quad i = 1, 2, \ldots, n \tag{18}$$

By normalizing, we obtain the normalized weight vectors:

$$W = \left(d(A_1), d(A_2), \ldots, d(A_n) \right)^T, \quad I = 1, 2, \ldots, n \ ) \tag{19}$$

W is a non-fuzzy number.

5.4. Data analysis with TOPSIS

The TOPSIS phase involves creating weighted matrices, calculating ideal solutions, assessing distances of alternatives from these solutions, and then scoring each based on similarity to the ideal solution. This approach is based on the Euclidean distance, which is a measure of the distance between two points [70,71,75] The TOPSIS Steps are presented below:

1. Establish the decision matrix: In this step, a decision matrix is constructed by associating each alternative with its performance values for each criterion. Attributes are listed according to their type in a matrix. The initial matrix X is as follows:

$$X = (X_{ij})m \times n = \begin{bmatrix} X_{11} & \cdots & X_{1N} \\ \vdots & \ddots & \vdots \\ X_{1N} & \cdots & X_{MN} \end{bmatrix} \qquad \textit{M attribute and N criteria}$$

with i = 1,2,….m and j = 1,2,….n

2. The matrix $(X_{ij})m \times n$ is then normalized to form the matrix r_{IJ}:

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{k=1}^{m} x_{kj}^2}} \quad \text{with i = 1,2,….m and j = 1,2,….n} \tag{20}$$

3. Calculate the weighted decision matrix:

$$t_{ij} = r_{ij}.w_j \text{ where i = 1,2,….m and j = 1,2,….n} \tag{21}$$

$$w_i = \frac{w_j}{\sum_{K=1}^{n} w_K} \text{ where j = 1,2,….n } \sum_{i=1}^{n} w_i = 1 \text{ Wj the origin weight}$$

4. Determine the worst alternative A^- and the best alternative A+:

$$A^- = (\mathrm{Max}(t_{ij} \ / \ i = 1,2, \ldots m \ / \ j \epsilon J_-); \mathrm{Min}(t_{ij} \ /i = 1,2, \ldots m/ \ j\epsilon J+) \equiv (twj \ / \ j=1,2 ,….n) \tag{22}$$

$$A^+ = (\mathrm{Min}(t_{ij} \ / \ i = 1,2, \ldots m \ / \ j\epsilon J^-); \mathrm{Max}(t_{ij} \ /i = 1,2, \ldots m/ \ j\epsilon J^+) \equiv (t_{bj} \ / \ j=1,2 ,….n) \tag{23}$$

J^+ = (1, 2,….n), associated with criteria having a positive impact.

J^- = (1,2,……n), associated with criteria having a negative impact.

5. Calculate the distance L^2 between the target alternative A^+ and the worst-case condition A^-

$$d_{iw} = \sqrt{\sum_{j=1}^{n}} \left(t_{ij} - t_{wj}\right)^2 \quad i=1, 2,….,m \tag{24}$$

$$d_{ib} = \sqrt{\sum_{j=1}^{n}} \left(t_{ij} - t_{bj}\right)^2 \quad i=1\ 2,….,m \tag{25}$$

where �je�D_{iw} and �je�D_{ib} are the L^2 norm distances relative to the target alternative with respect to the worst and best conditions, respectively.

6. Calculate the proximity factors and rank the alternatives based on S_{iw}:

$$S_{iw} = d_{iw}/(d_{iw} + d_{ib}), 0 \leq S_{iw} \leq 1, i = 1,2, \ldots m \quad (26)$$

S_{iw}= 1 if and only if the alternative solution has the best condition.
S_{iw}= 0 if and only if the alternative solution has the worst condition.

5.5. Performance indicators related to hub port competitiveness analysis.

International organizations (World Bank, UNCTAD, OECD) have established initiatives to develop indices for measuring global and regional port performance. These initiatives aim to enhance the competitiveness of ports by providing decision-makers with data to assess and compare port performance, identify strengths and weaknesses, and recognize areas for improvement. This collective effort promotes a unified approach to understand and improve port industry performance. These data, developed by various players, were explored to identify quantitative indicators suitable for each criterion, as presented in Table 3.

Table 3. Performance indicators for port criteria.

Category	Criteria	Indicator	Sources
Macroeconomic	Market size	Seaborne traffic in TEU	Collected from the port activity reports for the year 2021
	Maritime connectivity	Shipping connectivity index	Collected from UNCTAD database [76]
Technical	Port facilities	Quality of port infrastructure	Collected from OECD database [77]
	Port efficiency	Port performance index	World Bank port performance index [78]
Service	Value added	Added value of ports	Collected from various port activity reports for the year 2021
	Logistics activity	Logistics Performance Index (LPI)	World Bank Logistics Performance Index [56]
Cost	Handling costs	TCH	Collected from port sites in various reports for 2021
	Port costs	D&D load	Annual Benchmark Report: "Demurrage & Detention fees" [66]
Sustainability	CO2 emissions	Port CO2 emissions	Collected from various CSR reports for 2021
	Future capacity	Future capacity	Collected from port activity reports for 2021

6. Result of the case study

6.1. Identification and prioritization of selection criteria

To simplify the approach, a graphical representation was used to structure the problem in terms of objectives, categories, criteria, and decision alternatives. Figure 3 illustrates the hierarchy of selecting the port hub for serving our study area. At the first level of the hierarchy, the overall objective was clearly defined: to rank the defined hub ports. Level 2 consisted of the five dimensions used to evaluate container ports, and level 3 included the 10 criteria proposed as contributors to achieving the overall objective. Finally, level 4 grouped together the 10 container ports to be analyzed.

6.2. Defining weight of category and criteria

6.2.1. Questionnaire interviews

To apply our research methodology, we initially evaluated categories and criteria using judgement scales, developing an expert questionnaire based on the AHP method for levels 2 and 3 in Figure 3. To select our sample, we opted for a non-probability selective sampling approach, considering the predominance of three major alliances, which control more than 80% of the shipping market. This strategy guaranteed the representativity of our sample and the reliability of the results obtained. By involving experts from these dominant alliances to study the competitiveness of container ports in the Mediterranean and Europe, our analysis provided an enriching qualitative perspective. Non-probabilistic sampling is often preferred for qualitative studies that require a nuanced understanding of a specific subject. Despite the strengths of probabilistic methods in terms of generalizability, non-probabilistic techniques, particularly targeted sampling, are particularly suited for in-depth analyses on specialized topics, offering a better understanding of complex sector dynamics such as those related to port competitiveness [76]. Three shipping liner experts (X, Y, and Z) assessed these criteria. The goal was to understand the perspective of maritime companies' experts on five key categories and the importance of 10 criteria for container port competitiveness. They compared each criterion pair at every hierarchy level, selecting the more important one and rating its significance against the other, using Saaty's scale in Table 4 [77]**.** In these evaluations, respondents expressed their preferences between pairs on a scale of 1 to 9, following the AHP methodology.

Table 4. Triangular Fuzzy Scale of Saaty.

Saaty Scale	Triangular Fuzzy Scale	Fuzzy Scale
1	1 Equally Important (Eq. Imp.)	(1, 1, 1)
3	3 Slightly Important (S. Imp.)	(2, 3, 4)
5	5 Relatively Important (Rel. Imp.)	(4, 5, 6)
7	7 Very Important (V. Imp.)	(6, 7, 8)
9	9 Absolutely Important (Ab. Imp.)	(9, 9, 9)
2	Intermediate values between two adjacent scales.	(1, 2, 3)
4		(3, 4, 5)
6		(5, 6, 7)
8		(7, 8, 9)

6.2.2. Construction of the aggregated positive reciprocal fuzzy matrix

In the FAHP method, the initial stage is to evaluate the significance of each factor pair within a hierarchy. This is achieved by utilizing triangular fuzzy numbers and pairwise comparisons. Ratings of experts on the Saaty scale are transformed into fuzzy numbers, illustrated as (l, m, n) in Table 5 [78].

After the conversion of these ratings into fuzzy numbers, a 5x5 comparison matrix was created. This matrix included data from the experts' evaluations, showing how each factor was preferred over others. The same process was used for the third level of analysis, where a 2x2 matrix was created for each criterion in each category. This helped in organizing the preferences and weights at every level of the hierarchy. Finally, a fuzzy evaluation matrix for each respondent was built. This matrix, labeled $A = (a_{ij})_{n \times n}$, combines all the preferences and weights assigned by the experts, using fuzzy numbers. It provides a complete picture for decision-making in situations where there is uncertainty and subjectivity. By applying the equations (2), (3), (4), a judgement matrix was formed based on interview data. This matrix was then used for further analysis.

Table 5. Fuzzy Aggregated Matrix.

	Macroeconomic			Technique			Service			Cost			Sustainability		
	l_1	m_1	u_1	l_2	m_2	u_2	l_3	m_3	u_3	l_4	m_4	u_4	l_5	m_5	u_5
Macroeconomic	1.00	1.00	1.00	0.25	0.39	1.00	0.25	0.44	1.00	0.20	0.28	0.50	1.00	1.44	4.00
Technique	1.00	2.60	4.00	1.00	1.00	1.00	2.00	3.26	5.00	0.33	0.50	1.00	1.00	2.50	5.00
Service	1.00	2.27	4.00	0.20	0.31	0.50	1.00	1.00	1.00	0.33	0.50	1.00	1.00	2.60	4.00
Cost	2.00	3.59	5.00	1.00	1.99	3.00	1.00	1.99	3.00	1.00	1.00	1.00	1.00	3.14	5.00
Sustainability	0.25	0.70	3.00	0.20	0.40	1.00	0.25	0.39	1.00	0.20	0.32	1.00	1.00	1.00	1.00

6.2.3. Fuzzy extent value

Using equations (11) to (15) from section 5-3 on the matrix $A = (a_{ij})_{n*n}$ shown in Table 6, we obtained the results in Table 6.

Table 6. The fuzzy extent value.

	L	M	U
S1	0.04969325	0.07482264	0.11656442
S2	0.09815951	0.18144427	0.29447853
S3	0.06496933	0.1228735	0.19325153
S4	0.14723926	0.2301524	0.31288344
S5	0.03644172	0.04726403	0.08282209

6.2.4. Calculating the weight for each criterion and category

After applying formulas (16) to (19), we calculated the fuzzy values for each criterion as follows:
V(S1≥S2;S3;S4;S5)= min (0,25, 0,58 , 0,15 , 1)
V(S2≥S1;S3;S4;S5)=min (1 ,1 , 0,84 , 1)
V(S3≥ S1;S2;S4;S5)=min (1, 0,61,0,47,1)
V(S4≥S1;S2;S3;S5)=min (1 ,1 ,1 ,1)
V(S5≥S1;S2;S3;S4)= min(0.85, 0 ,19 ,0,47, 0,10)
The weight vector W for the five categories is (0,06, 0,33, 0,18, 0,39, 0,04).
Similarly, we calculated the weights of the criteria for each category.

6.2.5. Results of the FAHP calculation

6.2.5.1. The weight per category

Figure 4 shows the results of the FAHP analysis based on the assessments of experts in the region. It highlights the importance of costs (39%) and technical aspects (33%) in the competitiveness of ports, while also recognizing the importance of services (18%), macroeconomic factors (6%), and sustainability (4%).

According to the experts, operational costs are identified as the dominant factor influencing the selection of a port by shipping lines. This preeminence of costs, including both port and handling costs, is important because of their direct impact on the profitability and efficiency of shipping operations. Although other elements such as service quality and sustainability are important, they are often neglected due to the immediate need to minimize costs and optimize technical efficiency, which are directly measurable and have a tangible impact on the port's competitiveness. Experts also recognize that macroeconomic criteria are essential prerequisites for a port's competitiveness, providing a foundation on which other competitive strategies can be built. However, although fundamental, these dimensions are considered to have a less immediate impact on daily operational decisions, which may explain their lower position in the hierarchy of priorities. As for sustainability, although it is ranked at the bottom of experts' current priorities, it is important to note that the outlook for the sector is changing. Increasing awareness of environmental issues, coupled with regulatory pressures and consumer expectations, are beginning to raise the profile of sustainability in port strategies. In the long term, adopting sustainable practices could not only minimize environmental impacts but also offer a competitive advantage as ports become more responsive to stakeholder demands for greener operations.

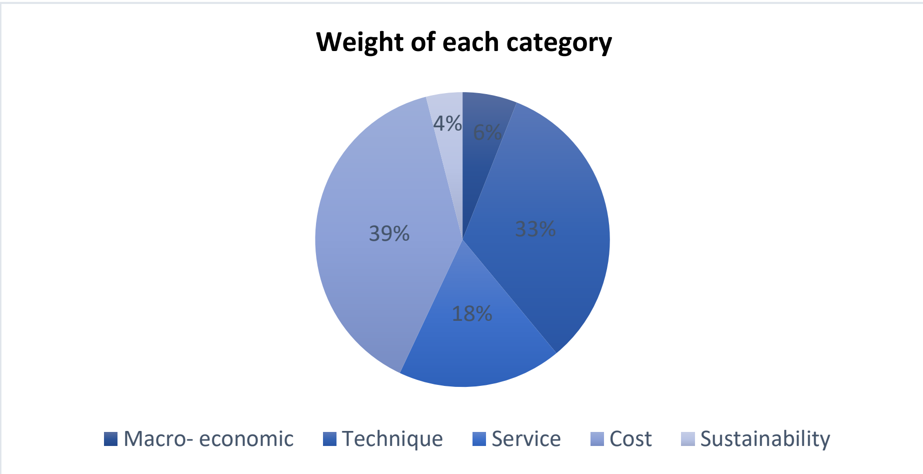

Figure 4. Weight of each category according to FAHP analysis.

6.2.5.2. The global weight per criteria

Through the FAHP (Fuzzy Analytic Hierarchy Process) analysis, weights were allocated to various criteria identified from the literature review, based on the insights of experts who have a deep understanding of the market and the current challenges that demand agility and resilience for sustaining profitability (Table 7). As illustrated in the table, the Cost category is prioritized with the highest weight of 39%, closely followed by the technical category at 33%, and Service at 18%, with Macroeconomic and Sustainability receiving lower weights of 6% and 4%, respectively. Among the criteria, Handling Costs are assigned the most critical, with a weight of 28%, followed by Operational Efficiency at 21%, Port Facilities at 12%, and Port Costs at 11%. Value Added and Logistics Performance are each allocated 9%, while the Environmental Aspect and Market Size are at the bottom of the ranking with 1%. In the discussion section, the analysis will concentrate on the top five ranked criteria and the lowest-ranked criteria to explore the reasons behind these rankings and to compare the findings with other similar studies.

Table 7. Weight by category and criteria.

Category	Weight	Criteria	Global Weight
Macroeconomic	6%	Market size	1%
		Maritime connectivity	5%
Technique	33%	Port facility	12%
		Port efficiency	21%
Service	18%	Port value added	9%
		Logistics performance (IPL)	9%
Cost	39%	Port cost	11%
		Handling costs	28%
Sustainability	4%	CO2 emission	1%
		Future capacity	3%

6.2.6. Result of TOPSIS for the final ranking of options

6.2.6.1. Defining the matrix decision

We created the decision matrix based on the different criteria we identified, and we assigned performance indicators to each criterion. The matrix was weighted according to the indicators in Table 8. The results of the first step of TOPSIS, using formula (20) from section 5-4, are shown in Table 8.

Table 8. Matrix normalized by criteria.

	Throughput Port 2021	LCSI 2021	Port Infrastructure Quality	efficiency	Value Added	Logistics performance	Handling Fees	Port Fees	Port Emissions CO2	Capacity Increase
Hamburg	0.3626	0.3515	0.3114	-0.0265	0.3037	0.3605	0.3565	0.5310	0.2374	0.3677
Antwerp	0.4949	0.4009	0.3353	0.1559	0.6509	0.3468	0.3492	0.3480	0.3738	0.4964
Bremerhaven	0.2067	0.2850	0.3114	0.2255	0.0930	0.3605	0.3696	0.5361	0.1162	0.3524
Rotterdam	0.5525	0.4122	0.3832	-0.0982	0.6819	0.3451	0.3492	0.3933	0.6921	0.4841
Tangier Med	0.2956	0.2925	0.3054	0.6066	0.0248	0.2180	0.3041	0.1434	0.3572	0.2911
Algeciras	0.1978	0.2919	0.3233	0.5305	0.0031	0.3287	0.3201	0.1995	0.1667	0.1869
Valencia	0.2303	0.3055	0.3233	0.0353	0.0001	0.3287	0.2910	0.1995	0.1364	0.2084
Gioia Tauro	0.1396	0.2459	0.2814	0.1105	0.0025	0.3210	0.2925	0.1657	0.0657	0.1287
Piraeus	0.1950	0.2705	0.2874	0.1516	0.0992	0.2747	0.1572	0.0963	0.1364	0.2206
Port Said	0.1964	0.2586	0.2874	0.4782	0.0006	0.2421	0.3201	0.1339	0.3385	0.1777

The results of the second step of TOPSIS, applying formula (21) from section 5-4, are presented in Table 9.

Table 9. Weighted and normalized matrix.

	Throughput Port 2021	LCSI 2021	Port Infrastructure Quality	Efficiency	Value Added	Logistics Performance	Handling Fees	Port Fees	Port Emissions CO2	Capacity Increase
Hamburg	0.002	0.019	0.038	-0.006	0.028	0.033	0.100	0.058	0.003	0.009
Antwerp	0.003	0.022	0.041	0.032	0.060	0.032	0.098	0.038	0.005	0.013
Bremerhaven	0.001	0.016	0.038	0.047	0.009	0.033	0.103	0.059	0.002	0.009
Rotterdam	0.003	0.023	0.046	-0.020	0.063	0.032	0.098	0.043	0.009	0.012
Tangier Med	0.002	0.016	0.037	0.126	0.002	0.020	0.085	0.016	0.005	0.007
Algeciras	0.001	0.016	0.039	0.110	0.000	0.030	0.090	0.022	0.002	0.005
Valencia	0.001	0.017	0.039	0.007	0.000	0.030	0.081	0.022	0.002	0.005
Gioia Tauro	0.001	0.014	0.034	0.023	0.000	0.029	0.082	0.018	0.001	0.003
Piraeus	0.001	0.015	0.035	0.031	0.009	0.025	0.044	0.011	0.002	0.006
Port Said	0.001	0.014	0.035	0.099	0.000	0.022	0.090	0.015	0.005	0.005

6.2.6.2. Euclidean distance for the alternatives of A+ and A-

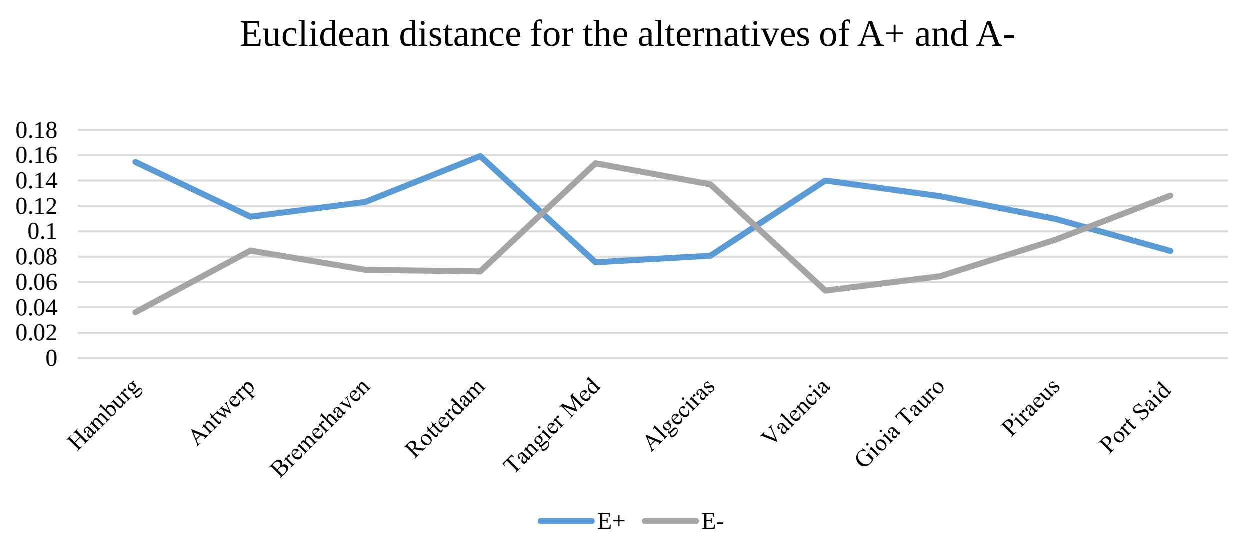

Figure 5. Euclidean distance for the alternatives of A+ and A-.

We have estimated the Euclidean distance based on formulae (22) and (25). The interpretation of Figure 7 allows us to confirm that the port of Tangier Med is both closest to the positive ideal solution and farthest from the negative ideal solution. According to TOPSIS, this would make Tangier Med the best choice among the options evaluated.

However, to obtain an overall ranking of the selected ports that considers both the proximity to the positive ideal and the distance from the negative ideal, we propose introducing a "Proximity Factor", which is defined by formula (26).

6.2.6.3. The ranking of ports competitiveness

The ranking of port competitiveness taking into consideration the selected 10 criteria was provided using equation (26), as shown in Table 10.

Table 10. The competitiveness ranking of the 10 ports.

Port	S	%	Ranking
Tangier Med	0.67	16%	1
Algeciras	0.63	15%	2
Port Said	0.60	14%	3
Piraeus	0.46	11%	4
Antwerp	0.43	10%	5
Bremerhaven	0.36	8%	6
Gioia Tauro	0.34	8%	7
Rotterdam	0.30	7%	8
Valencia	0.27	6%	9
Hamburg	0.19	4%	10

The TOPSIS analysis places Tangier Med (0.671) at the top, indicating alignment with the ideal solution. Algeciras (0.650) closely follows and is the main competitor to Tangier Med. Port Said (0.62) also occupies a competitive position. Piraeus (0.46) and Antwerp (0.43) are good but not as high-ranked as the top three ports. Bremerhaven, Gioia Tauro, Rotterdam, Valencia, and Hamburg round out the list. This ranking seems logical if we compare it with the incidence of transshipment in each port. We find a correlation of 73%.

A deeper analysis by assessing the 'proximity factor' for each category helped us rank the ports within each specific category. This analysis enables us to identify areas where the ports are performing well and areas where they require enhancements to boost their competitiveness along maritime routes. It offers a comprehensive perspective of each port's advantages and areas for development, providing clear insights for the formulation of new strategies aimed at increasing their competitiveness.

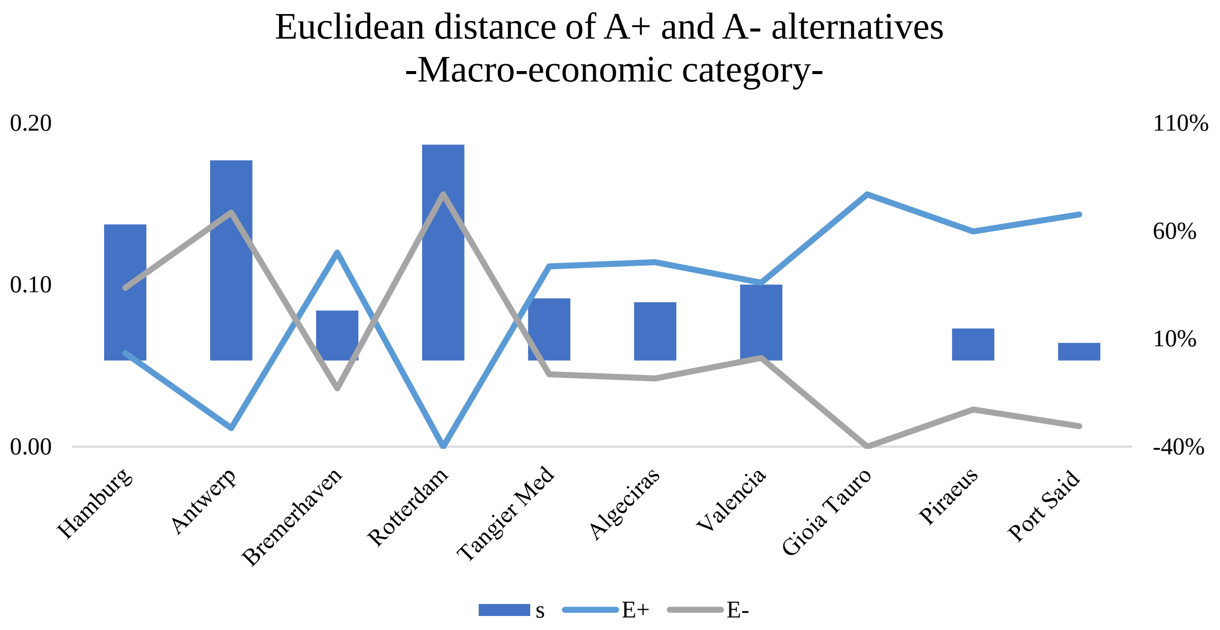

Figure 6. Proximity factors and Euclidian distance alternatives A+ and A- (Macroeconomic category).

Macroeconomic category (Figure 6): In the TOPSIS analysis for the macroeconomic category, which includes market size and connectivity, it is shown that Rotterdam stands out with an ideal performance. It demonstrates large markets and strong international connectivity. Antwerp also performs very well, but there is a slight margin for improvement. Ports such as Hamburg have performed well, but there is still room for improvement. Tangier Med, Valencia, Algeciras, and Bremerhaven are positioned at an intermediate level. On the other hand, Gioa Tauro shows the biggest gap from the ideal, and both Piraeus and Port Said require strategic improvements to enhance their macroeconomic competitiveness.

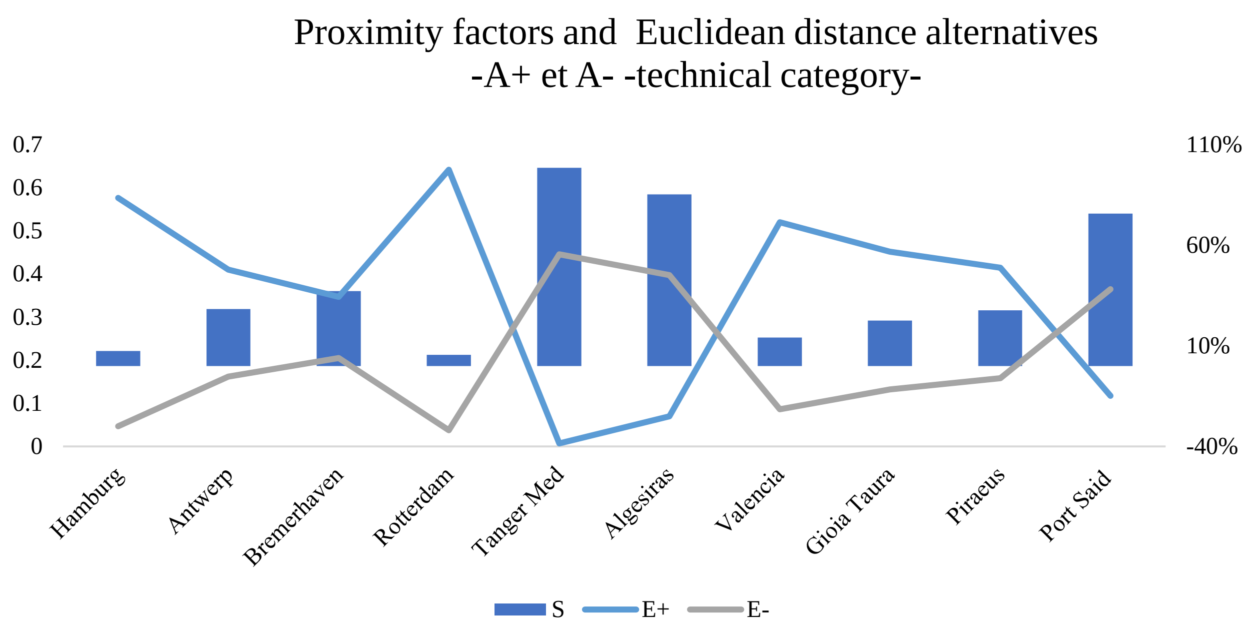

Figure 7. Proximity factors and Euclidean distance alternatives A+ and A- (Technical category).

Technical categories (Figure 7): The TOPSIS analysis ranks the best ports as follows: the port of Tangier leads, followed by the port of Algeciras, and then the port of Port Said. This indicates that they achieved the best results among the evaluated ports in terms of port facilities (weighted at 36%) and efficiency (weighted at 63%). Therefore, it appears that to improve their technical indicators, a port could benefit from strengthening both its port facilities and the efficiency of its operations. Meanwhile, Rotterdam and Hamburg show the biggest gap from the ideal.

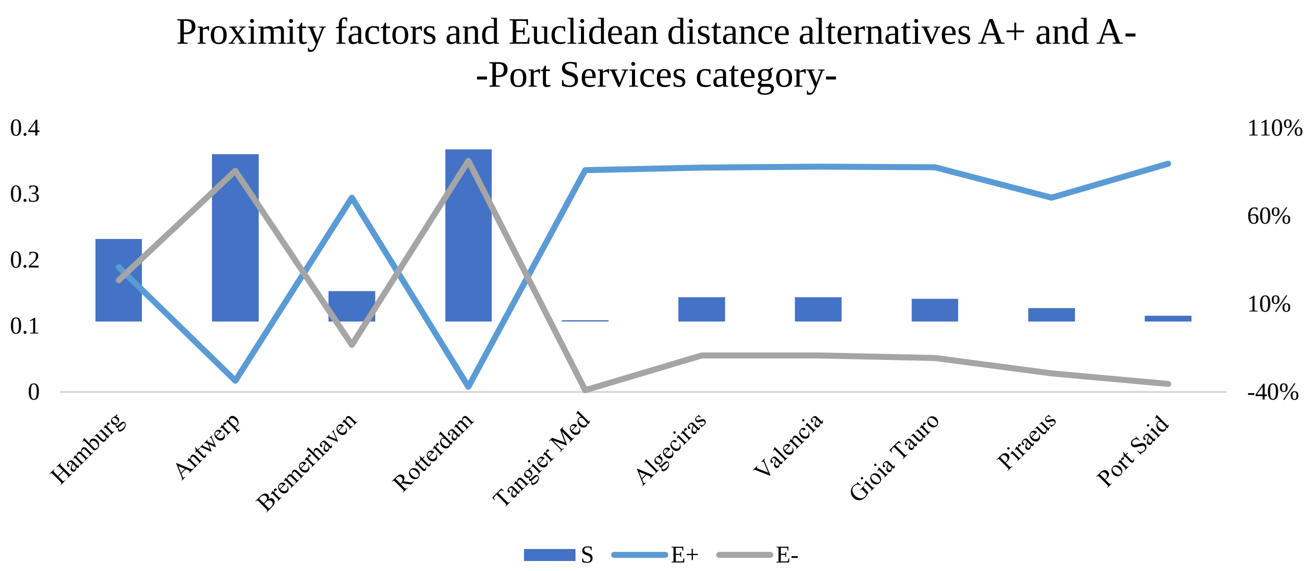

Figure 8. Proximity factors and Euclidean distance alternatives A+ and A- (Port Services category).

In the Port Services category (Figure 8), Rotterdam and Antwerp are in the lead, whilst the southern ports, including Tangier Med and Port Said, are less competitive overall, which could be attributed to challenges in terms of quality of service or less-developed value-added strategies compared with the northern ports.

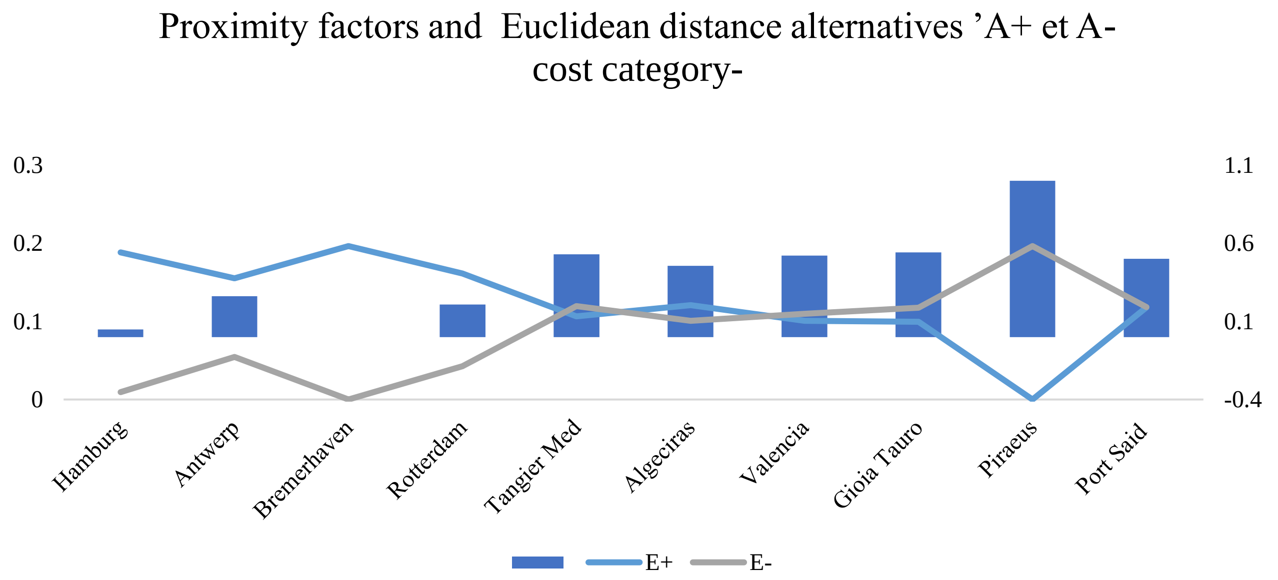

Figure 9. Proximity factors and1 Euclidean distance alternatives A+ and A- (Cost category).

In the context of port costs, the TOPSIS analysis results (Figure 9), which considered terminal handling costs (weighted at 0.72) and demurrage and detention (D&D) costs (weighted at 0.28), highlight Piraeus as a leader in cost competitiveness. Piraeus ports stand out with their lower rates compared to other studied ports, both in terminal handling and D&D costs. Businesses looking to cut logistics expenses might find Piraeus ports as top choices. Then, Tangier Med, Gioia Tauro, and Valencia ports rank 2nd, 3rd, and 4th. While not as cost competitive as Piraeus, they remain attractive for businesses seeking to balance costs with other key criteria like location, accessibility, services offered, etc. On the other hand, Northern European ports are less competitive in this aspect due to their relatively higher costs. Regarding the Cost category, we can thus classify the ports into three distinct categories:

- Piraeus: having the most favorable price conditions.
- Tangier Med, Algeciras, Valencia, and Port Said: having cost conditions that are neither too high nor too low.
- Hamburg, Antwerp, and Rotterdam: having unfavorable cost conditions.

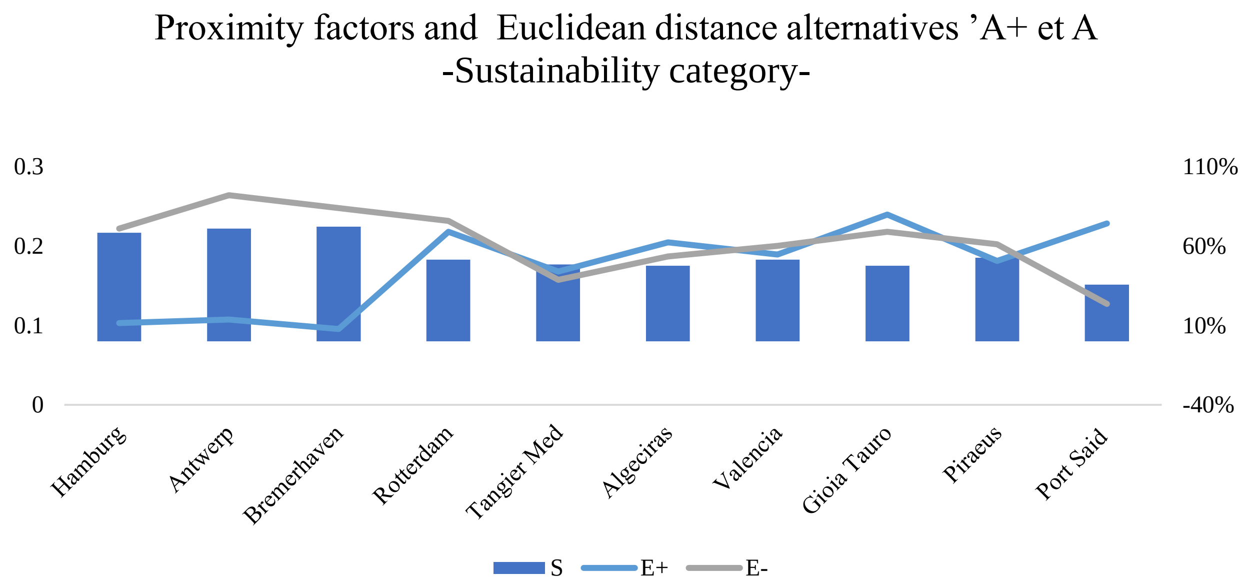

Figure 10. Proximity factors and Euclidean distance alternatives A+ and A- (Sustainability category).

In assessing port sustainability, the TOPSIS model considers two main factors: CO2 emissions in ports (35%), and the future growth capacity of ports (65%). According to this assessment (Figure 10), the ports of Northern Europe, in particular Bremerhaven, Hamburg, and Antwerp, stand out for their respect for the environment and their sustainability. They have shown an ability to grow while reducing their CO2 emissions.

The rankings in this case are very close, which could be explained by the fact that ports can adopt similar strategies to reduce their carbon footprint, such as using clean technologies, optimizing logistics, and investing in renewable energies. In terms of future capacity, a few measures have been implemented to increase terminal capacity. For example, PSA Antwerp's Europa terminal is being modernized with the acquisition of new automated handling cranes, and the "Digital Outer Weser" project in Bremerhaven aims to improve the use of available terminal capacity.

This global analysis reveals clear trends in port competitiveness. Northern European ports excel in terms of macroeconomics and services, while southern ports stand out for their technical aspects and competitive costs. Sustainability remains a key area for all ports, with significant efforts to reduce CO2 emissions and adopt sustainable practices.

7. Analysis and discussion

7.1. Main criteria defining the competitiveness of the hub port

The analysis of the main criteria has clearly shown that the competitiveness of the hub port is subject to numerous strategic factors based on the assessments of experts in the region. We will explore the first five in the following discussion.

The cost (39%) is obviously considered the most important aspect by experts when choosing a competitive hub port in the current context, since the cost is directly linked to profitability. This result aligns with the results of several previous studies, underscoring cost as a pivotal component in competitiveness analyses, with 537 mentions compared to other factors [8]. Particularly in an Asian context, cost significance prevails, receiving the highest weighting and followed closely by preferential incentives and operational environments [1]. Pricing strategies can enhance a port's competitive edge by reducing fees, including port dues and terminal handling charges. Specifically, the terminal handling cost (28%) is identified as the most important aspect by the experts. This shows that shipping companies focus more on costs at the terminals than overall port costs. The analysis of port tariffs further corroborates this, revealing that the cost of handling represents the most predominant element in the price structure, surpassing general port cost [5]. This reality has been unanimously confirmed by the experts. Shipping liners are actively working to reduce these significant charges to preserve their profit margins. This approach underlines the considerable impact of handling costs on the port economy and the need to adopt effective strategies to reduce them. In the same scope, a recent study has highlighted that port handling cost is a crucial strategic decision, directly affecting the viability and competitiveness of the port [79].

Following terminal handling costs, operational efficiency is the second most important factor. This result is in line with previous findings that confirm that efficiency is one of the most important factors in port competitiveness. For example, a recent research study confirmed that, from the perspective of shipping liners, the most important criterion was operational efficiency, followed by port service quality, geographical location, and accessibility [43]. Another study highlights the pivotal role of port infrastructure quality and logistics performance in enhancing a country's economic growth through better logistics services and increased seaborne trade. This underscores the importance of operational efficiency as a critical component of port competitiveness, contributing not only to the port's performance but also to broader economic benefits [80]. In addition, a survey conducted by other authors confirms that ranking port efficiency and performance is the top priority at 49.75%, followed by political stability at 23.48%. Port costs and infrastructure both came in third with a score of 9.54% each [46]. From a shipping liner perspective, port efficiency is an important key factor in choosing ports [38]. Furthermore, ranked third in importance, the quality of port infrastructure significantly impacts shippers' decision-making processes. Recent articles have discussed how improvements in port infrastructure can affect port selection by reducing transportation costs and improving service quality. This aspect is especially relevant for shipping companies, for whom operational efficiency, service quality, geographical location, and accessibility are critical factors in choosing ports [81].

Then, the port charges ranked in 4^{th} place of the global ranking. Indeed, multiple studies corroborate the significant impact with numerous studies confirming their substantial impact on decision-making. A study from the perspective of maritime companies has recently highlighted the importance of operational efficiency and cost-saving strategies as essential factors in selecting a hub port, by developing a port performance index and confirming the status of monetary cost (port charge) as one of the most important determinants in port choice [33]. In another article addressing competitiveness, the authors confirmed that a port can be more competitive if it is able to reduce port costs for users through higher productivity [82]. Within the Mediterranean port context, the authors confirm that the advantage of lower labor costs in nations along the Mediterranean's southern and eastern coasts has enabled their ports to offer specialized services at significantly reduced prices. This has positioned them as strong competitors to European ports. Shipping lines choose the most cost-effective hub ports mainly to reduce operating costs, increase profit margins, offer competitive rates, respond to market competition, optimize the logistics chain, and strategically position their vessels [83].

In equal fifth place, valued port and logistics services add a critical dimension to logistics competitiveness, with shipping lines favoring this criterion after costs and technical aspects [48]. This preference can be explained by the fact that the transshipment sector is marked by great instability, and that hubs are expected to evolve toward enriched services that go beyond the simple transfer of containers. The move toward the creation of logistics centers, encouraged by ESPO and illustrated by the example of Singapore, reflects proactive policies aimed at attracting high value-added companies, thereby enhancing the attractiveness and competitiveness of hubs through greater efficiency in cargo transit [84,85].

In terms of CO2 emissions, experts recognize the growing importance of sustainability in the port industry. Although perceived as less immediately influential on port selection decisions than other factors, the maritime industry currently focuses on efficiency and cost management. However, with increasing environmental concerns and regulations, this point will probably change. This observation is supported by the results of another study, which, from the perspective of shipping lines, ranked environmental aspects of port terminals as the least valued factor [86], although maritime companies and ports are committed to the IMO's environmental goals to limit global carbon emissions starting in 2021. Some ports adopt environmental management initiatives to comply with regulations, while others go beyond compliance by considering sustainability as a key element of their operational strategy [87]. In this regard, research suggests that sustainability is seen more as a factor of collaboration and complementarity, which requires extensive internal organizational work and collective commitment. In the transport and logistics sector, sustainability is increasingly viewed not as a competitive factor but as a crucial element of collaboration. Currently, ports are joining forces to meet the commitments set by the International Maritime Organization (IMO) and to incorporate these goals into the global agenda (CETMO, 2022). Additionally, the implementation of sustainable solutions in the maritime transport sector, while beneficial, faces several obstacles. Introducing innovations, such as low-sulfur fuel to reduce harmful emissions, involves challenges related to cost, availability, and industrial adaptation. Moreover, compliance with International Maritime Organization (IMO) regulations can lead to an increase in freight rates and delays due to the testing phases necessary for new technologies. These changes, essential for sustainable port development, require time, investment, and a balanced approach to not harm the sector's efficiency [88,89].

7.2. Port global ranking

The TOPSIS analysis has provided insight into the competitive dynamics of major hub ports in the Mediterranean and European market. By placing Tangier Med and Algeciras in the Strait of Gibraltar, along with Port Said at the Suez Canal, as leading international hub ports in the Mediterranean and European market, it demonstrates through concrete examples how ports located at key global chokepoints significantly contribute to enhancing the efficiency of international trade and global logistics networks [48]. Tangier Med is at the top due to its higher technical aspects, represented by port efficiency and infrastructure quality, and Algeciras follows closely, showcasing the intense competition and strategic importance of efficiency, cost, and infrastructure to secure market share. The TOPSIS ranking aligns with the competitive landscape of major transshipment ports, highlighting the strategic importance of port cost, efficiency, and infrastructure. The Port of Tangier-Med and the Port of Algeciras are excellent examples of this competition, demonstrating how ports can balance their advantage to have a significant market share. A recent study based on a multi-criteria analysis (MCA) to assess the competitiveness of the Tangier-Med and Algeciras ports revealed that Tangier-Med is the most attractive and excels in areas such as infrastructure, connectivity, port charges, and efficiency [90]. Similarly, further research on the competitive dynamics within the Strait of Gibraltar region highlights Tangier Med's position as a strong competitor to European hubs like Algeciras and Valencia. Both Tangier Med and Algeciras are hub ports with exceptionally high transshipment rates, indicating their important roles in global maritime logistics [91]. An in-depth comparison of Algeciras Bay, Rotterdam, New York-New Jersey, and Tangier Med on performance indicators, based on operational metrics like ship operations, cargo handling, and logistics services, provides insight into their relative operational efficiencies and capacities. The study confirmed that, for example, even if the Port of Rotterdam shows better performance compared to others, it is not necessarily more efficient than the Port of Tangier Med [92].

Port Said, ranked third in the list of port hubs, is a perfect illustration of its strategic importance in the Suez Canal. This privileged position is corroborated by several studies that underline its key role in the Mediterranean basin. The government, recognizing this importance, has undertaken initiatives to strengthen its position, notably through the development of infrastructure and the improvement of port efficiency [93]. Egypt's development strategy for Port Said includes not only expanding the terminals and increasing container handling capacity, but also improving customs connections and developing logistics. These efforts are aimed at transforming Port Said into a leading logistics hub, capable of meeting the growing demands of international maritime trade.

Regarding the lesser-ranked hub ports of Rotterdam, Hamburg, and Valencia, the results confirm that, despite their capacity, these ports have encountered challenges with their efficiency, attributable to various factors. Studies have analyzed reasons why ports face challenges such as a reduction in the number of ships and a decrease in freight volumes, exacerbated by pressure on resources and complex planning. This situation, resulting from the interdependence between stakeholders and the overutilization of infrastructure, leads to delays and affects the ports' efficiency and competitiveness [94]. The Port of Hamburg did not achieve a high ranking, primarily due to intense competition for transshipment traffic, especially around the Strait of Gibraltar, and significant disruptions caused by the COVID-19 pandemic. Despite these challenges, the Port of Hamburg maintains a critical role in international maritime trade, bolstered by its robust infrastructure, strategic positioning, and a strong focus on innovation and environmental sustainability. This situation highlights the competitive dynamics within European ports and the importance of continuous improvement and adaptation to global shipping trends [95]. Moreover, the ports of Northern Europe, despite their reputation for superior port infrastructure, scored lower in the technical aspect of the analysis, and have not been highly ranked in the Container Port Performance Index (CPPI) [96]. These ports have accumulated delays affecting their competitiveness in terms of port efficiency. This may be related to congestion problems in the ports of Northern Europe, which led to a massive decrease in carrier scales according to Alpha liner [97]. This result was supported by another study, which found that ports in Northern Europe are competitive but less efficient, due to over-investment in improving service. This research highlights the importance of ports for trade and the need for technical efficiency for competitiveness [98].

7.3. Main insight for the Southern Mediterranean range

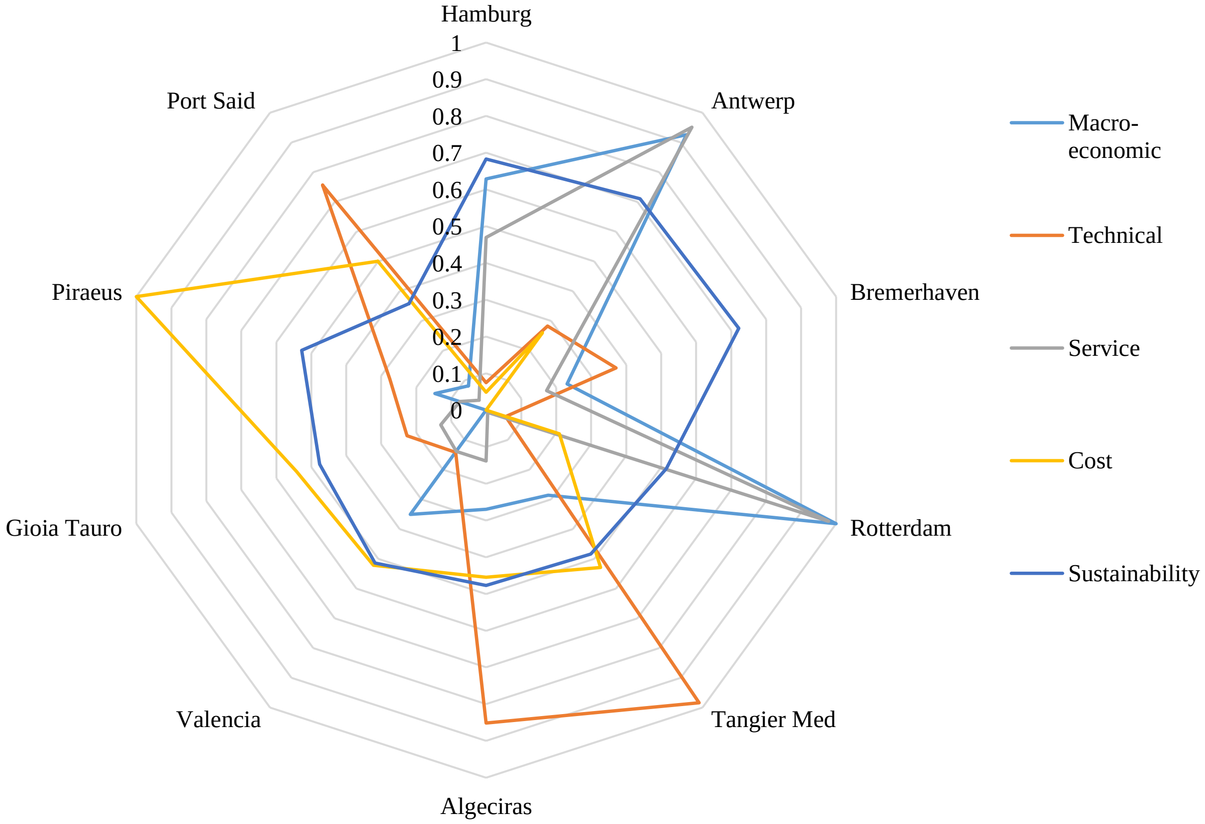

Figure 11. Results of the analysis by port.

The radar graph shown in Figure 11 evaluates the performance of major ports across five key areas: macroeconomic, technical, service, cost, and sustainability. It provides a complete view of each port's strengths and weaknesses, helping stakeholders to identify strong points and potential challenges.

This analysis highlights the strengths of each port in terms of their ranking in the studied area, but also identifies areas that need improvement. In this discussion, we will specifically focus on the ports of the Southern Mediterranean hub port Tangier Med and Port Said. Based on the results obtained, we will propose recommendations for these ports to strengthen their position in the global maritime industry.

The Port of Tangier Med, with the strategic support of the Moroccan government and TMSA, ranked 6th on the world container port performance index (CPPI) [96], making it the most efficient port in Europe and North Africa. It has regular connections to more than 180 ports in 70 countries and offers weekly services to around 40 ports in 22 African countries [99,100]. Tangier Med has launched major development initiatives, such as technology partnerships to improve operational efficiency and sustainability, as well as a strong push toward digitalization and the introduction of new maritime services [101]. These efforts aim to strengthen its competitive position in the global port industry, despite having lower port throughput and maritime connectivity compared to Northern European ports [99]. However, Tangier Med faces competition from these Northern European ports and is seeking to consolidate its position through continued expansion and optimization of its operations.

The Port of Port Said, at the Suez Canal's northern entrance, is a critical Eastern Mediterranean hub, ranked 15th globally in the 2021 World Bank's Container Port Performance Index. Established in 1999 and encompassing a 145 km² Suez Canal Economic Zone with industrial and logistics areas, it offers extensive facilities for various cargo types. Managed by the Suez Canal Container Terminal (SCCT), it aims to attract global shipping companies, serving as a significant commercial transit hub in the region [102].

To improve the competitiveness of ports in North Africa, it is recommended that a strategic approach be adopted focusing on internationalization, the development of intermodality, integration into sustainable development initiatives, and the optimization of pricing strategies.

Internationalization Strategies: North African ports, such as Tangier Med, could explore internationalization strategies to enhance their maritime connectivity. Inspired by the ports of Rotterdam and Antwerp, which have invested in ports in emerging markets like Oman, Brazil, and India, these ports might consider similar investments or other forms of collaboration, such as consultancy and training services with strategically located ports [84]. The Chinese "Belt and Road" initiative also illustrates the significance of internationalization strategies through the creation of provincial port groups and the development of international strategic partnerships [103].

Development of Intermodality: The development of intermodality is important to go beyond transshipment volumes and explore land systems through rail intermodality in Africa. Previous studies have highlighted the importance of intermodality for the creation of port added value [104]. Integrating ports into land transport networks improves logistics efficiency and contributes to a more sustainable supply chain [49].

Integration into Sustainable Development Initiatives: The port of North Africa should be integrated into international sustainable development initiatives and create joint projects with neighboring countries. This involves adopting environmentally responsible practices and contributing to sustainable development goals, ensuring port management minimizes environmental impact and fosters sustainable economic growth. For example, reflecting the influence of the Southern Mediterranean ports, Tangier Med and Port Said have been incorporated into the European Union's carbon quota system under the "Fit for 55" package.

8. Conclusion

In conclusion, this comprehensive analysis has underscored the multifaceted nature of port competitiveness in the Mediterranean and Northern Europe, revealing a complex interplay of factors that range from operational costs and technical efficiency to sustainability practices, services aspects, and macroeconomic conditions. The FAHP analysis, based on expert assessments, highlighted costs and technical aspects as paramount in determining port competitiveness, a finding that resonates with the current market dynamics where efficiency and cost-effectiveness are key drivers of choice for shipping lines.

Furthermore, the analysis highlights the growing importance of sustainability within the port industry. While initially considered less influential on port selection decisions, environmental concerns and regulations are prompting a shift towards more sustainable operations. This evolution suggests a move from viewing sustainability as merely a regulatory compliance issue to considering it as a core component of a port's operational strategy and a collaborative effort within the maritime sector.

The TOPSIS analysis further refined our understanding of port competitiveness, placing Tangier Med, Algeciras, and Port Said at the forefront of the Mediterranean and European markets. These ports, leveraging their strategic locations and technical efficiency, represent the critical balance required between cost, efficiency, and strategic infrastructure investment to maintain and enhance their positions in the global maritime landscape. Tangier Med, with its superior technical aspects such as port efficiency and infrastructure quality, and Algeciras, demonstrate the critical role of efficiency, cost, and infrastructure in securing market share. Meanwhile, Port Said's strategic positioning in the Suez Canal underscores its significant role within the Mediterranean basin. However, the challenges faced by other hubs like Rotterdam, Hamburg, and Valencia, primarily due to efficiency issues, highlight the competitive pressures within European ports and the necessity for continuous improvement and adaptation to global shipping trends.

The study's findings offer a roadmap for ports seeking to improve their competitiveness. By focusing on operational efficiency, cost in port, strategic infrastructure development, and sustainability initiatives, ports can navigate the challenges and opportunities of the global maritime industry more effectively. Moreover, the insights provided by the FAHP and TOPSIS analyses serve as a valuable benchmark for ongoing and future research into port competitiveness. They underscore the necessity for ports to adopt a holistic approach that encompasses not only immediate operational concerns but also long-term strategic and environmental objectives.

As the maritime industry continues to evolve, driven by technological advancements, regulatory changes, and shifting global trade patterns, the ability of ports to adapt and innovate will remain critical. The competitive dynamics of ports in the Mediterranean and Northern Europe, as detailed in this study, offer a compelling glimpse into the future of global maritime logistics and trade, highlighting the imperative for strategic resilience and sustainable growth in the face of ever-changing market demands.

In addition, the study provides useful information for shipping companies to assist them in making an appropriate choice of port, as well as for policy-makers and port authorities striving to increase competitiveness and sustainability in the maritime sector. It illuminates the comparative advantages and opportunities of each port examined.

Moreover, the study reveals some limitations as it has been restricted to major hub ports, omitting growing ports which could also hold significant roles in regional economies. Additionally, the data used in this research to assess the competitiveness levels of maritime ports was limited to a single year due to several data availability constraints, and the data used came from different sources, which may introduce variations and biases. Therefore, it would be relevant in future studies to use a broader set of ports with time series or even qualitative data based on expert opinions regarding their views on each port.

Use of AI tools declaration

The authors declare that they have not used artificial intelligence (AI) tools in the creation of this article.

Conflict of interest

The authors declare that there are no conflicts of interest.

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