EVALUATING PORT PERFORMANCE IN EU COUNTRIES WITH FUZZY AND GREY LOGIC

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Resume

Ports are fundamental components of global supply chains, and their performance is critical to sustaining international trade and economic activity. Recognizing that existing studies often focus on individual ports rather than broader regional patterns, a new hybrid Multi-Criteria Decision-Making (MCDM) model is proposed to provide a more comprehensive assessment framework. Based on expert judgments, the Fuzzy Analytic Hierarchy Process (AHP) results indicate that cargo type is the most influential determinant, followed by cargo direction and container volume. Using Evaluation based on Distance from Average Solution - Grey (EDAS-G) and Additive Ratio Assessment - Grey (ARAS-G), the port performance across 24 EU countries for the period 2014-2023, incorporating a temporal dimension that enables multi-year trend analysis. The hybrid grey-based ranking shows that Italy, Spain, the Netherlands, and Germany rank the highest, while Slovenia, Bulgaria, Malta, and Cyprus consistently rank at the lower end.

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1 Introduction

Ports are among the most crucial components of global trade. They play a vital role in maritime trade [1-2]. The efficiency of ports directly impacts a country's export performance and, consequently, its economic development [3]. Therefore, accurate predictions of port performance require comprehensive research, and such studies are crucial for the sector [4]. However, significant gaps remain in the existing literature on ports in certain areas [5]. Closing these gaps is crucial because improving port efficiency directly impacts global trade and the global supply chain by increasing efficiency [6].

Research into improving the port efficiency is highly valuable for the industry [7]. Some ports are known to increase their efficiency levels by effectively utilizing their resources. However, not all the ports exhibit this characteristics; some fail to utilise their resources effectively [8]. Therefore, it is essential to compare ports to assess the sector's overall situation and identify the efficient and inefficient ones.

The existing literature on ports is generally dominated by studies focusing on a single port. Conversely, comparative studies are limited, leaving a significant gap in this field [9]. In this regard, a comprehensive approach is adopted in this study, similar to that used by Moros-Daza et al. (2025) [2]. This study is based on findings from an MCDM analysis of port performance across 24 EU countries. The primary objective of the study was to shed light on the dynamics of EU port performance by addressing the following research questions:

RQ1: What are the relative weights of the criteria affecting the performance of ports in EU member states?

RQ2: How do countries' performance rankings change according to the identified criteria?

In this study is adopted a new hybrid MCDM model. The primary reason for choosing this approach was the multidimensional nature of port performance and the inadequacy of existing single method approaches to encompass all these dimensions. The study provides a comprehensive analysis of a 10-year dataset. Criteria weights were determined using the Fuzzy AHP method, which reveals the relative importance of indicators affecting the port performance. Subsequently, the port performance of EU countries was evaluated using the

EDAS-G and ARAS-G methods together, revealing how their rankings changed across different reference points. Combining effective analytical logic for addressing uncertainty with grey system theory, which can handle missing and insufficient data, increases the reliability of the evaluation process. Furthermore, the proposed hybrid model is tested through sensitivity analyses to enhance its robustness.

2 Literature research

2.1 Port

Ports play a strategic role in ensuring the effective operation of the global supply chain. Therefore, analyzing port efficiency levels and identifying the most suitable alternatives is vital for decision-makers. In this context, the MCDM methods are powerful tools that facilitate the rational, systematic selection of alternatives. The MCDM methods are widely used in literature to select the best option from among various alternatives (e.g., [10-14]. There is extensive literature on the use of MCDM methods in port-related decision-making processes. The section presents various recent studies from the literature that address the application of MCDM methods in port analysis.

For example, Ilyas et al. (2024), [15] and Ur Rehman and Ali (2021), [16] evaluated China's energy supply route options using transport corridors and ports, applying MCDM methods. Similarly, Bagocius et al. (2014) used an MCDM approach to determine the optimal location for an LNG port in the Baltic Sea [17]. Furthermore, researchers from various disciplines have employed these methods for port selection, comparative port analysis, and regional port functionality, taking into account various geographic, economic, and operational criteria.

Kine et al. (2025) used the geographic information systems and MCDM methods together to determine suitable locations for dry cargo ports. The study's findings reveal that the two most decisive criteria in port location selection are distance to the highway and distance to the railroad. On the other hand, the distance to an existing port was identified as the least important factor [18].

Kolakowski et al. (2024) analyzed Polish ports regarding bunkering. Their research was focused on determining the most suitable port and fuel type for this process. The research data were obtained using the Delphi technique and analysed using MCDM. Based on expert opinions, three main factors were identified: access to market supply and demand, supply chain reliability, and delivery security. According to the analysis, the Port of Swinoujscie is the leading port for refueling [19].

Wang and Li (2023) addressed sustainability issues in ports. In the first stage, nine sustainability-related criteria were evaluated using the MCDM method. The Step-wise Weight Assessment Ratio Analysis (SWARA) and Weighted Aggregated Sum and Product Assessment (WASPAS) methods were employed in this evaluation process. In the second stage, cities that could minimise economic, environmental, and social costs were identified as suitable locations for dry ports. The analysis revealed that the key regions for dry ports were Suzhou, Chongqing, Chengdu, Wuhan, Changsha, Wuxi, and Hefei. It also showed that shippers operating in regions close to ports prefer road transportation, whereas those in more distant regions prefer rail [20].

Garg et al. (2023) evaluated Chinese ports using the fuzzy AHP model, an MCDM method. Of the six factors identified for measuring port sustainability performance, environmental considerations, digitalisation, automation, and strategy were deemed the most significant. The researcher emphasises that the results of the MCDM can inform the strategic decision-making processes of sector managers and policymakers [21].

Ighravwe and Mashao (2023) evaluated Nigerian ports within the framework of the security criterion. In the analysis, the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) and WASPAS methods from MCDM were used in conjunction. The evaluation was based on five key criteria: human security; property security and monitoring capabilities; resilience and flexibility against regular and irregular threats; and measures to address physical security breaches. The analysis reveals that human security is the most critical criterion. According to the TOPSIS ranking, Apapa Port was identified as the highest-performing port, while Onne Port ranked lowest in the evaluation [22].

Pamucar and Gorcun (2022) used a hybrid Fuzzy LBWA-CoCoSo'B method to evaluate European ports. According to the research findings, the port cost stands out as the most effective criterion. According to the port performance ranking, the Port of Antwerp ranked first, achieving the highest score. At the same time, the Port of Barcelona ranked the lowest in line with the evaluated criteria [23].

Lamii et al. (2022) analyzed risk factors in ports. In the research process, literature review, Delphi technique, and MCDM method were used, respectively. AHP, a MCDM technique, was used to reveal the complex structure of port systems. The risk factors were then prioritized according to the identified criteria. The findings show that human and economic-based risk factors are critical for ports. Such risk factors can disrupt port business processes. Gorcun (2021) analyzed the efficiency of Black Sea container ports through MCDM methods. Two different models were used in the research. The first model combines Entropy and Operational Competitiveness Rating Analysis (OCRA) methods, whereas the second model combines Entropy with the Technique for Order Preference by Similarity to Ideal Solution (EATWIOS) method. The study has two main objectives. The first one is to determine whether the MCDM methods used are effective evaluation tools in the maritime sector. The second one is to analyze the comparative performance of the Black Sea ports. Nine input and four output criteria were used in the performance evaluation. According to the final ranking, Constanza Port is the highest-performing port among the nine ports analyzed [24-25].

Kannika et al. (2019) evaluated Thailand's port system from a sustainability perspective. In the analysis process, BWM and MCDM methods were used together. The evaluation criteria are grouped under three main headings: economic, environmental, and social. The study's results reveal that cost efficiency is the most important criterion. High-quality service and infrastructure investments follow this criterion [26].

Clearly, the MCDM methods are widely favoured in both academic and practical contexts of port management and strategic planning. A review of the relevant literature reveals that MCDM approaches have become increasingly important in port analyses, providing a systematic basis for decision-making processes.

2.2 EU, Port and MCDM

Various studies have evaluated European countries using different MCDM approaches. For instance, Burhan (2024), [27] assessed EU member states with VIKOR (VlseKriterijumska Optimizacija I Kompromisno Resenje) and Multi-Attribute Ideal-Real Comparative Analysis (MAIRCA) based on nine criteria, including air emissions, RandD investment, high-speed internet accessibility, patent applications, the number of RandD personnel, modal split in transport, and education levels. The 2023 VIKOR results ranked Sweden, Germany, and France as the top performers, while the MAIRCA results identified Sweden, Germany, and Denmark as the top performers.

As this example illustrates, both the selection of criteria and the choice of the MCDM techniques vary substantially across studies. Due to this methodological diversity, it is rare to encounter research that uses the same dataset and model configuration. Accordingly, no directly comparable study was identified in existing literature.

3 Methodology

In this study, a new hybrid MCDM model is proposed to evaluate the port performance of the EU countries. In this context, the criterion weights were calculated using the Fuzzy AHP method. The ranking of alternatives was performed using both the EDAS-G and ARAS-G methods. The steps of the methods used in this study are presented below.

3.1 Fuzzy AHP

The AHP has been utilized in numerous studies for years to address MCDM problems. However, a decision maker's evaluation may often be fuzzy and uncertain. In such cases, it may not be possible to obtain the decision maker's assessment unambiguously through the AHP's traditional pairwise comparison method [28]. The fuzzy AHP enables decision-makers to express their evaluations using fuzzy numbers rather than relying on precise numerical values [29]. Fuzzy AHP addresses these challenges by structuring the decision-making process within a hierarchical framework and identifying a compromise solution among competing criteria [30]. Given the uncertainty and imprecision inherent in expert judgments on port performance criteria, this approach provides a more realistic and reliable weighting structure; therefore, the Fuzzy AHP method was preferred in this study. Triangular Fuzzy Numbers (TFNs) are preferred for representing linguistic variables, and this method facilitates comparisons.

The fuzzy AHP method is implemented in the following steps [31]:

Step 1. Definition of Object and Goal Sets with Degree Analysis Initialization

Let $X=\{x_1,x_2,\dots,x_n\}$ be an object set and $U=\{u_1,u_2,\dots,u_n\}$ be a goal set. Degree analysis (g_i) is applied for each target with respect to each criterion. The TFN M_1 are used to express the M degree analysis value associated with the targets.

$$S_i=\sum_{j=1}^{m} M_{gi}^{j}\otimes\left[\sum_{i=1}^{n}\sum_{j=1}^{m} vM_{gi}^{j}\right]^{\{-1\}}, \tag{1}$$

g_i provides the TFN associated with the j-th target based on the i-th criterion.

Step 2. Calculation of the Degree of Possibility Between Triangular Fuzzy Numbers

M_1, shown with (l_1,m_1,u_1) parameters and M_2, (l_2,m_2,u_2). The degree of possibility is defined as,

$$V(M_2\geq M_1)=\sup_{y\geq x}\left[\min\left(\mu_{M_1}(x),\mu_{M_2}(y)\right)\right], \tag{2}$$

$$V(M_2\geq M_1)=hgt(M_1\cap M_2)=\mu_{M_2}(d)=\\=\begin{cases}1, \ if\ m_2\geq m_1\\ 0, \ if\ l_1\geq u_2\\ \dfrac{l_1-u_2}{(m_2-u_2)-(m_1-l_1)}, otherwise,\end{cases} \tag{3}$$

where d is the ordinate of the point D where μ_{M_1} and μ_{M_2} cross.

Step 3. Computation and Normalization of the Fuzzy Significance Vector

Significance vector is calculated indicated as $W'=(d'(A_1),d'(A_2),\dots,d'(A_{nT}))^T\ i=\{1,2,\dots,n\}$ and vector normalized applied. $W'=(d(A_1),d(A_2),\dots,d(A_n))^T\ i=\{1,2,\dots,n\}$ vector is calculated as significance vector where $d'(A_i)=\min V(S_i\geq S_k)$.

Table 1 *Statement and TFN, [32]*

Statement	TFN
Equal Importance (EI)	(1,1,1)
Moderate importance (MI)	(1,3,5)
Strong Importance (SI)	(3,5,7)
Very Strong Importance (VSI)	(5,7,9)
Extreme Importance (EXI)	(7,9,11)

Table 1 presents the linguistic statements and their corresponding TFNs used in the analysis.

3.2 EDAS-G

The EDAS method is a reliable and versatile tool for decision-making processes that require systematic evaluation [33]. The main feature of the EDAS method is its two distance measures: Positive Distance from Mean (PDA) and Negative Distance from Mean (NDA). The EDAS-G was developed by Stanujkic et al. (2017) [34]. Grey numbers represent the minimum and maximum expected performance ratings of the alternative against each criterion. The EDAS-G method provides more consistent and reliable results by evaluating alternatives against both positive and negative ideal solutions in MCDM problems involving uncertainty. Since the port performance data often contain incomplete, imprecise, or fluctuating values across years and countries, the grey extension of EDAS offers a more robust structure for handling uncertainty; therefore, the EDAS-G method was preferred in this study**.**

The steps of EDAS-G are implemented in the following stages [34]:

Step 1. Forming The Matrix for Grey Decision-Making (Y)

$$\otimes Y = \begin{bmatrix} [\underline{y}_{11}, \bar{y}_{11}] & [\underline{y}_{12}, \bar{y}_{12}] & \cdots & [\underline{y}_{1n}, \bar{y}_{1n}] \\ [\underline{y}_{11}, \bar{y}_{11}] & [\underline{y}_{22}, \bar{y}_{22}] & \cdots & [\underline{y}_{2n}, \bar{y}_{2n}] \\ \cdots & \cdots & \cdots & \cdots \\ [\underline{y}_{m1}, \bar{y}_{m1}] & [\underline{y}_{m2}, \bar{y}_{m2}] & \cdots & [\underline{y}_{mn}, \bar{y}_{mn}] \end{bmatrix}. \tag{4}$$

Step 2. Determine The Grey Average Answer

$$\otimes Y_j^\circ = ([\underline{y}^\circ_1, \bar{y}_1^\circ],[\underline{y}^\circ_2, \bar{y}_2^\circ],\cdots[\underline{y}^\circ_n, \bar{y}_n^\circ]). \tag{5}$$

Step 3. Determination of the Grey Distances from the Average Solution. The Grey positive distance from the mean is obtained using the formula, $\otimes d_{ij}^{+} = [\underline{d}_{ij}^{+}, \bar{d}_{ij}^{+}]$ and the Grey negative distance from average $\otimes d_{ij}^{-} = [\underline{d}_{ij}^{-}, \bar{d}_{ij}^{-}]$,

$$\underline{d}_{ij}^{+} = \begin{cases} \dfrac{\max(0,(\underline{y}_{ij} - \bar{y}_j^\circ))}{0.5(\underline{y}^\circ_j + \bar{y}_j^\circ)}; & j \in \Omega_{\max} \text{ and} \\ \dfrac{\max(0,(\underline{y}^\circ_j - \bar{y}_{ij}))}{0.5(\underline{y}^\circ_j + \bar{y}_j^\circ)}; & j \in \Omega_{\min} \end{cases}, \tag{6}$$

$$\bar{d}_{ij}^{+} = \begin{cases} \dfrac{\max(0,(\underline{y}_{ij} - \bar{y}_j^\circ))}{0.5(\underline{y}^\circ_j + \bar{y}_j^\circ)}; & j \in \Omega_{\max} \text{ and} \\ \dfrac{\max(0,(\underline{y}^\circ_j - \bar{y}_{ij}))}{0.5(\underline{y}^\circ_j + \bar{y}_j^\circ)}; & j \in \Omega_{min} \end{cases}, \tag{7}$$

$$\underline{d}_{ij}^{-} = \begin{cases} \dfrac{\max(0,(\underline{y}^\circ_j - \underline{y}_{ij}))}{0.5(\underline{y}^\circ_j + \bar{y}_j^\circ)}; & j \in \Omega_{\max} \text{ and} \\ \dfrac{\max(0,(\underline{y}_{ij} - \bar{y}_j^\circ))}{0.5(\underline{y}^\circ_j + \bar{y}_j^\circ)}; & j \in \Omega_{min} \end{cases}, \tag{8}$$

$$\bar{d}_{ij}^{-} = \begin{cases} \dfrac{\max(0,(\underline{y}^\circ_j - \underline{y}_{ij}))}{0.5(\underline{y}^\circ_j + \bar{y}_j^\circ)}; & j \in \Omega_{\max} \text{ and} \\ \dfrac{\max(0,(\bar{y}_{ij} - \underline{y}^\circ_j))}{0.5(\underline{y}^\circ_j + \bar{y}_j^\circ)}; & j \in \Omega_{\min} \end{cases}, \tag{9}$$

Step 4. Determine the Weighted Grey Distances for PDA and NDA. The grey PDA's weighted sum by using the formula $\otimes Q_i^{+} = [\underline{Q}_i^{+}, \overline{Q}_i^{+}]$ and the grey NDA's weighted sum, $\otimes Q_i^{-} = [\underline{Q}_i^{-}, \overline{Q}_i^{-}]$

$$\underline{Q}_i^{+} = \sum_{j=1}^{n} w_j \underline{d}_{ij}^{+}, \tag{10}$$

$$\overline{Q}_i^{+} = \sum_{j=1}^{n} w_j \overline{d}_{ij}^{+}, \tag{11}$$

$$\underline{Q}_i^{-} = \sum_{j=1}^{n} w_j \underline{d}_{ij}^{-}, \tag{12}$$

$$\overline{Q}_i^{-} = \sum_{j=1}^{n} w_j \overline{d}_{ij}^{-}. \tag{13}$$

Step 5. Determine the Representative (Typical) Scores of Alternatives. Each alternative's weighted sums of the Grey PDA and Grey NDA should be set to their typical values.

$$\underline{S}_i^{+} = \frac{\underline{Q}_i^{+}}{\max_k \overline{Q}_k^{+}}, \tag{14}$$

$$\overline{S}_i^{+} = \frac{\overline{Q}_i^{+}}{\max_k \overline{Q}_k^{+}}, \tag{15}$$

$$\underline{S}_i^{-} = 1 - \frac{\overline{Q}_i^{-}}{\max_k \overline{Q}_k^{+}},, \tag{16}$$

$$\underline{S}_i^- = 1 - \frac{\underline{Q}_i^-}{\max\limits_k \overline{Q}_k^+}, \tag{17}$$

Step 6. Determine the Appraisal Score S_i

$$S_i = \frac{1}{2}\left[(1-\alpha)\left(\underline{S}_i^- + \underline{S}_i^+\right) + \alpha\left(\overline{S}_i^- + \overline{S}_i^+\right)\right]. \tag{18}$$

Step 7. Determination of the Best Alternative Based on S_i Scores. Rank the options based on the evaluation score's declining values. The best option is the one with the highest S_i.

3.3 ARAS-G

In the ARAS methodology, a utility function is employed to evaluate the intricate relative efficiency of a prospective alternative. This utility function directly quantifies the efficacy of the alternatives by contemplating the cumulative impact of the values and weights assigned to the pivotal criteria within the dilemma [35]. The ARAS methodology, conceived by Turskis and Zavadskas (2010), is predicated on juxtaposing the utility function values of the alternatives against the utility function value of the optimal alternative, in contrast to other MCDM approaches [36-37]. Since the ARAS-G can effectively handle uncertainty and provides stable rankings through its utility-based structure, it was preferred in this study.

The stages of the ARAS-G methodology proposed by Turskis and Zavadskas (2010) are elucidated below [36]:

Step 1. Formulation of the Grey Decision-Making Matrix

$$\otimes X = [\![\otimes x_{ij}]\!]_{mxn} = \begin{bmatrix} [\otimes x_{01}] & [\otimes x_{02}] & \dots & [\otimes x_{0n}] \\ [\otimes x_{11}] & [\otimes x_{12}] & \dots & [\otimes x_{1n}] \\ [\otimes x_{21}] & [\otimes x_{22}] & \dots & [\otimes x_{2n}] \\ \vdots & \vdots & \ddots & \vdots \\ [\otimes x_{m1}] & [\otimes x_{m2}] & & [\otimes x_{mn}] \end{bmatrix}; \tag{19}$$

$i = 0, 1, \dots m$;
$j = 1, 2 \dots n$;

where m is the number of alternatives, n number of criteria, $\otimes x_{ij}$ is the grey number, which represents the performance value of the i_{th} alternative in terms of the j_{th} criterion, finally $\otimes x_{0j}$ is the optimal value of j_{th} criterion. If the optimal value of j_{th} criterion is unknown, then optimal value of j calculated as follows:

If the preferred values of the criterion are the maxima (benefit)

$$\otimes x_{0j} = \max_i \otimes x_{ij}. \tag{20}$$

If the preferred values of the criterion are the minima (cost)

$$\otimes x_{0j} = \min_i \otimes x_{ij}. \tag{21}$$

Step 2. Construction of the Normalized Grey Decision-Making Matrix

$$\otimes \overline{X} = [\![\otimes \bar{x}_{ij}]\!]_{mxn} = \begin{bmatrix} [\otimes \bar{x}_{01}] & [\otimes \bar{x}_{02}] & \dots & [\otimes \bar{x}_{0n}] \\ [\otimes \bar{x}_{11}] & [\otimes \bar{x}_{12}] & \dots & [\otimes \bar{x}_{1n}] \\ [\otimes \bar{x}_{21}] & [\otimes \bar{x}_{22}] & \dots & [\otimes \bar{x}_{2n}] \\ \vdots & \vdots & \ddots & \vdots \\ [\otimes \bar{x}_{m1}] & [\otimes \bar{x}_{m2}] & & [\otimes \bar{x}_{mn}] \end{bmatrix}; \tag{22}$$

$i = 0, 1, \dots m$;
$j = 1, 2 \dots n$.

The criteria, whose preferred values are the maxima, are normalized as follows

$$\otimes \bar{x}_{ij} = \frac{\otimes x_{ij}}{\sum_{i=0}^{m} \otimes x_{ij}}. \tag{23}$$

The criteria, whose preferred values are the minima, are normalized as follows

$$\otimes x_{ij} = \frac{1}{\otimes x_{ij}^*}, \ \otimes \bar{x}_{ij} = \frac{\otimes x_{ij}}{\sum_{i=0}^{m} \otimes x_{ij}}. \tag{24}$$

Step 3. Formulation of the Normalized-Weighted Grey Decision Matrix

$$\otimes \hat{X} = [\![\otimes \hat{x}_{ij}]\!]_{mxn} = \begin{bmatrix} [\otimes \hat{x}_{01}] & [\otimes \hat{x}_{02}] & \dots & [\otimes \hat{x}_{0n}] \\ [\otimes \hat{x}_{11}] & [\otimes \hat{x}_{12}] & \dots & [\otimes \hat{x}_{1n}] \\ [\otimes \hat{x}_{21}] & [\otimes \hat{x}_{22}] & \dots & [\otimes \hat{x}_{2n}] \\ \vdots & \vdots & \ddots & \vdots \\ [\otimes \hat{x}_{m1}] & [\otimes \hat{x}_{m2}] & & [\otimes \hat{x}_{mn}] \end{bmatrix}; \tag{25}$$

$i = 0, 1, \dots m$;
$j = 1, 2 \dots n$;
$\otimes \hat{x}_{ij} = \otimes \bar{x}_{ij} \cdot \otimes w_j, \ \ i = 0, 1, \dots, m.$

Step 4. Determination of the Values of the Optimality Function

$$\otimes S_i = \sum_{j=1}^{n} \otimes \hat{x}_{ij}, \tag{26}$$

where $\otimes S_i$ is the grey value of the optimality function of i-th alternative. The performance degree of alternatives can be assessed according to this $\otimes S_i$ value.

$\otimes S_i$ remains a grey number; to convert a grey value to a crisp value, several methodologies exist. In this manuscript, the centre-of-area method is employed for transforming a grey value to a crisp value.

$$S_i \frac{1}{2}(\otimes S_i(\underline{l}, \overline{u})), i = 0, 1, \dots, m. \tag{27}$$

Step 5. Calculation of the Utility Degree

$$K_i = \frac{S_i}{S_0}, i = 1, 2, \dots, m, \tag{28}$$

where S_i and S_0 represent the optimality criteria values, derived from Equation (28).

The intricate relative efficiency of the reasonable alternative can be assessed in accordance with the utility function values.

***Table 2** Summary of mathematical symbols and notation used in the study*

Symbol	Description
(l,m,u)	Triangular fuzzy number: lower-middle-upper values
M_j^i	Fuzzy pairwise comparison value between criteria *i* and *j*
$V(M_1 \geq M_2)$	Degree of possibility that one fuzzy number is greater than another
S_i	Significance value of criterion *i* (before normalization)
w_i	Normalized weight of criterion *i*
$\underline{y}^{\circ}_{ij} + \bar{y}^{\circ}_{ij}$	Grey performance interval of alternative *i* under criterion *j*
$\underline{A}_j + \overline{A}_j$	Grey average value for criterion *j*
SP_i	Weighted grey PDA value for alternative *i*
SN_i	Weighted grey NDA value for alternative *i*
TSO_i, TSN_i	Typical (crisp) values of weighted PDA and NDA
AS_i	Appraisal score of alternative *i*
x_i	Optimal value of criterion *j* (benefit/cost)
n_{ij}	Normalized grey value in ARAS-G
S_i	Optimality function value (grey)
S_j^*	Crisp optimality value (center-of-area)
K_i	Utility degree of alternative *i*

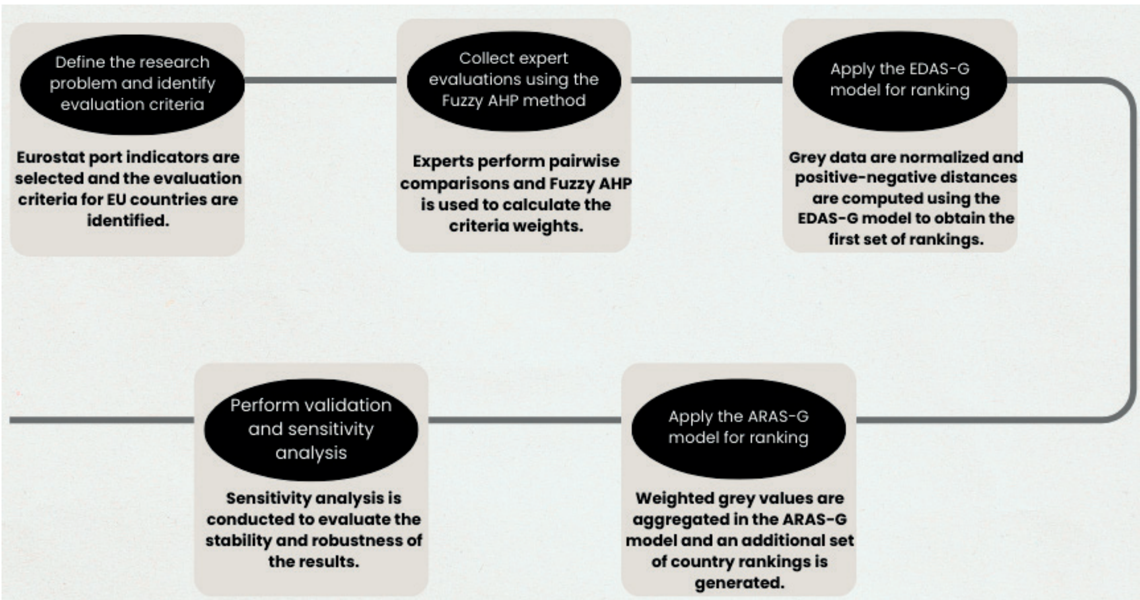

***Figure 1** Flow chart of the proposed model*

The mathematical symbols and notation employed within the Fuzzy AHP, EDAS-G, and ARAS-G procedures are systematically presented in Table 2.

4 Dataset and the application

Eurostat published its data 10 times: for the years 2014, 2015, 2016, 2017, 2018, 2019, 2020, 2021, 2022, and 2023 [38]. These data are published in two categories: quarterly and annually. In this study, the port performance is assessed through a multidimensional set of operational, economic, and environmental indicators. Since the data for some EU countries is not consistent from year to year, 24 countries were considered as alternatives. The fuzzy AHP method was used to weight the criteria. Among various MCDM methods, fuzzy AHP is the most widely used for addressing complex problems [39]. Fuzzy logic is compelling in solving complex problems that involve predictive thinking and decision-making processes [40]. Decision makers can flexibly express their opinions across different value ranges and represent their indecision numerically [41].

The flowchart of the proposed model is presented in Figure 1. The definitions of the criteria used in this study are shown in Table 3. These criteria encompass the

Table 3 *Criteria list, [38]*

Criteria	Definitions	Type
C1-Number of ship arrivals and departures	Vessels arriving at main ports by type	Benefit
C2-Container volume	Containers handled in main ports by loading status	Benefit
C3-Passenger traffic	Passengers embarked and disembarked in all ports	Benefit
C4-Cargo direction	Gross weight of goods by inwards and outwards movements	Benefit
C5-Cargo type	Gross weight of goods handled in main ports by cargo type	Benefit
C6-GDP	Gross domestic product (GDP) at current market prices	Benefit
C7-Air pollutants	Air pollutants by source sector	Cost
C8-Municipal waste management	Municipal waste by waste management operations	Benefit
C9-Share of renewable energy	Share of energy from renewable sources	Benefit

Table 4 *Fuzzy AHP-Based aggregated pairwise evaluation of criteria*

	C1	C2	C3	C4	C5	C6	C7	C8	C9
C1	(1.000, 1.000, 1.000)	(0.723, 0.433, 0.336)	(2.853, 5.078, 7.164)	(0.815, 0.695, 0.653)	(0.373, 0.206, 0.143)	(1.332, 1.442, 1.533)	(2.141, 4.360, 6.434)	(2.853, 5.078, 7.164)	(2.141, 4.360, 6.434)
C2	(1.377, 2.290, 2.942)	(1.000, 1.000, 1.000)	(4.076, 6.119, 8.139)	(0.903, 0.744, 0.688)	(0.465, 0.228, 0.154)	(1.549, 1.525, 1.572)	(2.408, 4.514, 6.544)	(3.000, 5.000, 7.000)	(3.000, 5.000, 7.000)
C3	(0.347, 0.196, 0.138)	(0.244, 0.161, 0.121)	(1.000, 1.000, 1.000)	(0.292, 0.174, 0.126)	(0.186, 0.133, 0.106)	(0.541, 0.373, 0.302)	(1.000, 0.641, 0.525)	(1.000, 0.642, 0.525)	(1.000, 0.330, 0.200)
C4	(1.222, 1.425, 1.513)	(1.105, 1.330, 1.445)	(3.380, 5.711, 7.841)	(1.000, 1.000, 1.000)	(0.581, 0.391, 0.315)	(1.715, 2.537, 3.147)	(2.141, 4.360, 6.434)	(2.954, 5.165, 7.237)	(2.667, 4.829, 6.882)
C5	(2.954, 5.165, 7.237)	(2.141, 4.360, 6.434)	(5.348, 7.361, 9.369)	(1.719, 2.531, 3.160)	(1.000, 1.000, 1.000)	(1.835, 2.667, 3.276)	(2.408, 4.514, 6.544)	(3.323, 5.348, 7.361)	(3.323, 5.348, 7.361)
C6	(0.746, 0.686, 0.647)	(0.641, 0.654, 0.626)	(1.838, 2.662, 3.289)	(0.579, 0.392, 0.313)	(0.540, 0.373, 0.301)	(1.000, 1.000, 1.000)	(1.243, 2.141, 2.798)	(1.552, 3.680, 5.720)	(1.243, 2.141, 2.798)
C7	(0.465, 0.228, 0.154)	(0.412, 0.221, 0.150)	(1.000, 1.549, 1.904)	(0.465, 0.228, 0.154)	(0.412, 0.221, 0.150)	(0.800, 0.465, 0.353)	(1.000, 1.000, 1.000)	(1.000, 1.933, 2.627)	(0.801, 0.464, 0.355)
C8	(0.347, 0.196, 0.138)	(0.330, 0.200, 0.140)	(1.000, 1.552, 1.904)	(0.337, 0.192, 0.137)	(0.299, 0.186, 0.133)	(0.642, 0.270, 0.173)	(1.000, 0.514, 0.381)	(1.000, 1.000, 1.000)	(0.801, 0.299, 0.186)
C9	(0.465, 0.228, 0.154)	(0.330, 0.200, 0.140)	(1.000, 3.000, 5.000)	(0.373, 0.206, 0.143)	(0.299, 0.186, 0.133)	(0.800, 0.465, 0.353)	(1.246, 2.137, 2.809)	(1.246, 3.323, 5.348)	(1.000, 1.000, 1.000)

key environmental, economic, and operational aspects of port activity to the extent permitted by data availability and comparability across EU countries.

4.1 Results obtained from the Fuzzy AHP

The importance levels of the criteria were determined by a group of five port experts (two academics from the Department of International Trade and Logistics, a Professor in Marketing, a Manager of an International Logistics Firm, and a Director of an International Port). There are studies in the literature that suggest the five decision makers are sufficient, and these studies were conducted with this number [42-44]. The linguistic expressions used by the decision makers were converted into triangular fuzzy numbers, and the evaluations were combined using geometric averaging to create a joint decision matrix. The resulting fuzzy AHP-based aggregated pairwise evaluation of the criteria is presented in Table 4. After applying the fuzzy AHP steps to the data, the weights of the Port Performance indicators are determined. The results are presented in Table 5.

According to the analysis results, the most important criterion is "Cargo Type," with a weight of 29%. This is followed by "Cargo Direction" (22%), "Container Volume" (21%), and "Number of Ship Arrivals and

***Table 5** Fuzzy AHP weight results for port performance indicators*

Criteria	W	%
C1	0.183	0.18
C2	0.214	0.21
C3	0.000	0.00
C4	0.217	0.22
C5	0.293	0.29
C6	0.063	0.06
C7	0.000	0.00
C8	0.000	0.00
C9	0.030	0.03

***Table 6** Grey decision matrix, criteria C_1 to C_3*

	C1	C2	C3
Belgium	(69, 1270)	(9726, 13192)	(22303, 25886)
Bulgaria	(1, 6)	(195, 282)	(2855, 3451)
Denmark	(30859, 44226)	(750, 1080)	(268047, 361601)
Germany	(16373, 31412)	(12680, 15918)	(104925, 117120)
Estonia	(8213, 15057)	(204, 288)	(28730, 32091)
Ireland	(814, 2867)	(797, 1176)	(11428, 12587)
Greece	(40895, 74956)	(3983, 6329)	(362036, 515899)
Spain	(14283, 34324)	(14358, 17663)	(136661, 204514)
France	(10445, 26638)	(4572, 6387)	(41967, 64092)
Croatia	(18779, 34142)	(138, 442)	(195657, 285456)
Italy	(55147, 86530)	(10247, 13080)	(381820, 505968)
Cyprus	(5, 76)	(300, 417)	(1818, 3179)
Latvia	(249, 1072)	(359, 479)	(5025, 6680)
Lithuania	(280, 368)	(350, 1051)	(4211, 5123)
Malta	(7955, 14622)	(77, 134)	(23288, 45967)
Netherlands	(857, 2010)	(11719, 15539)	(34997, 42488)
Poland	(1905, 2787)	(1793, 3107)	(14543, 18678)
Portugal	(551, 2147)	(2649, 3309)	(12002, 14189)
Romania	(0, 1)	(643, 830)	(3968, 5356)
Slovenia	(0, 34)	(676, 1048)	(1397, 2138)
Finland	(7089, 19514)	(1199, 1441)	(23997, 32175)
Sweden	(14020, 30523)	(1451, 1639)	(66785, 82191)
Norway	(1724, 6640)	(727, 915)	(54942, 71354)
Turkey	(289, 2233)	(8146, 12591)	(48685, 65846)

Departures" (18%), reflecting their substantial influence on operational and logistical performance. The GDP plays a moderate role with a weight of 6%, while the Share of Renewable Energy contributes minimally (3%). The Passenger Traffic, Air Pollutants, and Municipal Waste Management receive zero weight, indicating no significant effect within this evaluation structure. These zero-weight outcomes are common in fuzzy AHP studies and have similarly been reported in previous research [45-48]. Grey numbers were generated from data published over 10 years periods (2014-2023). For each country in the alternative list, the maximum and minimum values constituted the lower and upper values. The generated decision matrix was evaluated using both the EDAS-G and ARAS-G methods to obtain robust performance rankings.

4.2 Results obtained from the EDAS-G

After determining the criterion weights, grey numbers representing each country's performance during the specified time period were calculated for each criterion. The application of grey numbers

***Table 7** Grey decision matrix, criteria C_4 to C_6*

	C4	C5	C6
Belgium	(237852, 288827)	(237359, 288827)	(403003, 596321)
Bulgaria	(25258, 30997)	(25258, 30997)	(43024, 94709)
Denmark	(91382, 98230)	(76402, 87880)	(265635, 382309)
Germany	(267837, 303742)	(267837, 303742)	(2927430, 4185550)
Estonia	(23010, 43578)	(22040, 40172)	(20365, 38188)
Ireland	(47483, 55120)	(46325, 52636)	(200818, 520935)
Greece	(167036, 194468)	(145928, 180296)	(167539, 225197)
Spain	(427672, 497812)	(427672, 497812)	(1038949, 1498324)
France	(271964, 308629)	(266859, 303757)	(2153733, 2822455)
Croatia	(18551, 23607)	(14529, 21435)	(44284, 78048)
Italy	(443141, 509397)	(433598, 499193)	(1627405, 2128001)
Cyprus	(6948, 10268)	(6948, 10259)	(17482, 31340)
Latvia	(36153, 71836)	(33974, 70261)	(22790, 39072)
Lithuania	(37237, 52462)	(37237, 52462)	(36410, 73793)
Malta	(3370, 7211)	(3370, 7211)	(8948, 20542)
Netherlands	(545105, 607527)	(545105, 607525)	(678627, 1067599)
Poland	(68744, 136410)	(68107, 135977)	(408714, 748923)
Portugal	(79371, 93356)	(78956, 91916)	(173053, 267384)
Romania	(43753, 69250)	(42598, 68654)	(150528, 324369)
Slovenia	(18012, 23127)	(18012, 23127)	(37270, 63951)
Finland	(95640, 120488)	(93606, 118143)	(205855, 273318)
Sweden	(159611, 179949)	(159611, 179949)	(435641, 551781)
Norway	(193605, 225781)	(180267, 199621)	(322823, 425446)
Turkey	(378688, 535825)	(378688, 535825)	(626785, 1030514)

***Table 8** Grey decision matrix, criteria C_7 to C_9*

	C7	C8	C9
Belgium	(5860, 9770)	(406, 755)	(8, 15)
Bulgaria	(13450, 27410)	(334, 467)	(18, 23)
Denmark	(9740, 11660)	(759, 844)	(29, 44)
Germany	(168100, 278210)	(606, 648)	(14, 22)
Estonia	(5500, 12320)	(303, 389)	(26, 41)
Ireland	(4320, 9810)	(531, 631)	(9, 15)
Greece	(50700, 85860)	(488, 524)	(15, 25)
Spain	(31170, 161230)	(448, 482)	(16, 25)
France	(23370, 35440)	(497, 558)	(14, 22)
Croatia	(2450, 5320)	(377, 430)	(27, 31)
Italy	(20360, 37060)	(423, 462)	(17, 20)
Cyprus	(2790, 6960)	(488, 596)	(9, 20)
Latvia	(3270, 4440)	(351, 461)	(37, 44)
Lithuania	(4790, 6980)	(412, 467)	(24, 32)
Malta	(290, 2800)	(565, 748)	(5, 15)
Netherlands	(10510, 20450)	(468, 533)	(5, 17)
Poland	(90050, 206210)	(272, 370)	(11, 17)
Portugal	(11630, 22350)	(442, 545)	(30, 35)
Romania	(11980, 44290)	(216, 288)	(24, 26)
Slovenia	(2720, 6690)	(257, 429)	(21, 25)
Finland	(14330, 29150)	(468, 630)	(39, 51)
Sweden	(10630, 13150)	(390, 452)	(51, 66)
Norway	(1980, 2260)	(414, 799)	(68, 77)
Turkey	(266430, 368670)	(352, 398)	(13, 18)

Table 9 The result of the EDAS-G

	$\otimes Q_i^+$	$\otimes Q_i^-$	$\otimes S_i^+$	$\otimes S_i^-$	Rank
Belgium	(0.393, 1.520)	(1.241, 4.792)	(0.109, 0.221)	(0.930, 0.965)	6
Bulgaria	(0.000, 0.001)	(0.000, 0.003)	(0.716, 0.999)	(0.683, 0.773)	22
Denmark	(0.322, 0.587)	(1.014, 1.850)	(0.318, 0.561)	(0.822, 0.899)	9
Germany	(0.844, 2.307)	(2.662, 7.275)	(0.000, 0.019)	(0.994, 1.000)	4
Estonia	(0.000, 0.022)	(0.000, 0.068)	(0.632, 0.949)	(0.699, 0.799)	17
Ireland	(0.000, 0.002)	(0.000, 0.006)	(0.554, 0.882)	(0.720, 0.824)	19
Greece	(0.507, 1.281)	(1.599, 4.040)	(0.027, 0.210)	(0.933, 0.991)	7
Spain	(1.288, 3.009)	(4.062, 9.488)	(0.000, 0.016)	(0.995, 1.000)	2
France	(0.393, 1.007)	(1.240, 3.175)	(0.026, 0.161)	(0.949, 0.992)	8
Croatia	(0.179, 0.421)	(0.563, 1.329)	(0.590, 0.816)	(0.741, 0.813)	10
Italy	(1.659, 3.153)	(5.230, 9.942)	(0.002, 0.015)	(0.995, 0.999)	1
Cyprus	(0.000, 0.000)	(0.000, 0.000)	(0.781, 1.064)	(0.663, 0.752)	24
Latvia	(0.008, 0.025)	(0.024, 0.079)	(0.584, 0.945)	(0.700, 0.815)	16
Lithuania	(0.000, 0.011)	(0.000, 0.036)	(0.612, 0.946)	(0.700, 0.806)	20
Malta	(0.000, 0.000)	(0.000, 0.000)	(0.727, 1.048)	(0.667, 0.770)	23
Netherlands	(1.422, 2.800)	(4.484, 8.830)	(0.074, 0.172)	(0.945, 0.976)	3
Poland	(0.000, 0.024)	(0.000, 0.076)	(0.196, 0.739)	(0.766, 0.938)	14
Portugal	(0.000, 0.015)	(0.000, 0.047)	(0.344, 0.671)	(0.787, 0.891)	15
Romania	(0.000, 0.004)	(0.000, 0.014)	(0.548, 0.903)	(0.714, 0.826)	18
Slovenia	(0.000, 0.003)	(0.000, 0.011)	(0.708, 0.997)	(0.684, 0.775)	21
Finland	(0.010, 0.033)	(0.032, 0.105)	(0.318, 0.668)	(0.788, 0.899)	13
Sweden	(0.024, 0.150)	(0.075, 0.474)	(0.099, 0.352)	(0.888, 0.969)	12
Norway	(0.052, 0.242)	(0.163, 0.762)	(0.153, 0.350)	(0.889, 0.952)	11
Turkey	(0.743, 2.241)	(2.344, 7.066)	(0.027, 0.141)	(0.955, 0.991)	5

facilitates performance assessment of alternatives and incorporates a temporal dimension into the evaluation process [49]. Interval series containing upper and lower limits can be interpreted as grey numbers. Representing uncertain data with upper and lower bounds provides more information than the traditional real numbers [50]. The Grey decision matrix is shown in Table 6.

The weighted and normalized weighted grey aggregates of PDA and NDA, derived from the application of Equation (10) to (17), are presented in Table 9. The subsequent phase involves ranking the options. Values of the criteria functions for the alternatives S_i were computed using Equation (18). Values S_i and the ultimate ranking of the alternatives are likewise illustrated in Table 9.

4.3 Results obtained from the ARAS-G

The ranking of the alternatives was obtained directly from the decision matrix in Tables 6-8 using the obtained criterion weights, and the calculation procedure outlined in Equations (19) - (28) was applied. As presented in Table 10, the ARAS-G results provide the final ranking of the alternatives.

5 Sensitivity analysis

The sensitivity analysis can be performed by changing the criterion weights [51]. In this study, the sensitivity analysis, approach widely used in the literature, was adopted, and the model's stability was tested through the two alternative scenarios: equalizing the criterion weights and interchanging the highest and lowest weights [52-53]. The first scenario assumes the criteria weights are equal. The second is the scenario in which the criterion weights for the highest and lowest weights are interchanged. The results obtained from the two different scenarios are shown in Table 11.

The sensitivity analysis results indicate only limited changes in rankings between the two scenarios. While equalizing and redistributing the criteria weights may result in small shifts in the positions of some countries, the overall structure of the rankings is largely preserved, confirming the model's stability. For instance, Italy, Spain, and Germany consistently appeared among the highest-performing countries across both Scenario 1 and Scenario 2 in both EDAS-G and ARAS-G results. Turkey, Sweden, and the Netherlands also showed steady performance patterns, maintaining similar rank intervals under both weighting schemes.

Similarly, the lowest-performing countries exhibited

Table 10 *The result of the ARAS-G*

	S_s	K_s	Ranking
Optimal	0.1608		
Belgium	0.0611	0.3800	8
Bulgaria	0.0055	0.0345	22
Denmark	0.0419	0.2606	9
Germany	0.0901	0.5602	4
Estonia	0.0087	0.0541	20
Ireland	0.0113	0.0704	16
Greece	0.0697	0.4331	6
Spain	0.1114	0.6928	2
France	0.0629	0.3912	7
Croatia	0.0243	0.1512	12
Italy	0.1286	0.7996	1
Cyprus	0.0028	0.0172	24
Latvia	0.0099	0.0618	18
Lithuania	0.0089	0.0554	19
Malta	0.0041	0.0257	23
Netherlands	0.1081	0.6720	3
Poland	0.0218	0.1358	13
Portugal	0.0205	0.1275	15
Romania	0.0110	0.0685	17
Slovenia	0.0058	0.0360	21
Finland	0.0216	0.1344	14
Sweden	0.0357	0.2220	11
Norway	0.0371	0.2304	10
Turkey	0.0870	0.5407	5

Table 11 *The result of the sensitivity analysis*

	Proposed Model		Scenario 1		Scenario 2	
	EDAS-G	ARAS-G	EDAS-G	ARAS-G	EDAS-G	ARAS-G
Belgium	6	8	9	11	5	9
Bulgaria	22	22	24	24	22	24
Denmark	9	9	8	7	8	11
Germany	4	4	2	2	4	5
Estonia	17	20	16	18	18	22
Ireland	19	16	18	19	17	18
Greece	7	6	5	4	6	6
Spain	2	2	3	3	2	2
France	8	7	6	6	9	10
Croatia	10	12	11	13	10	12
Italy	1	1	1	1	1	1
Cyprus	24	24	20	22	19	21
Latvia	16	18	14	16	13	14
Lithuania	20	19	19	20	15	19
Malta	23	23	15	12	14	3
Netherlands	3	3	4	5	3	4
Poland	14	13	23	17	24	20
Portugal	15	15	17	15	20	15
Romania	18	17	22	23	23	23
Slovenia	21	21	21	21	16	16
Finland	13	14	13	14	21	17
Sweden	12	11	12	10	12	13
Norway	11	10	10	9	11	8
Turkey	5	5	7	8	7	7

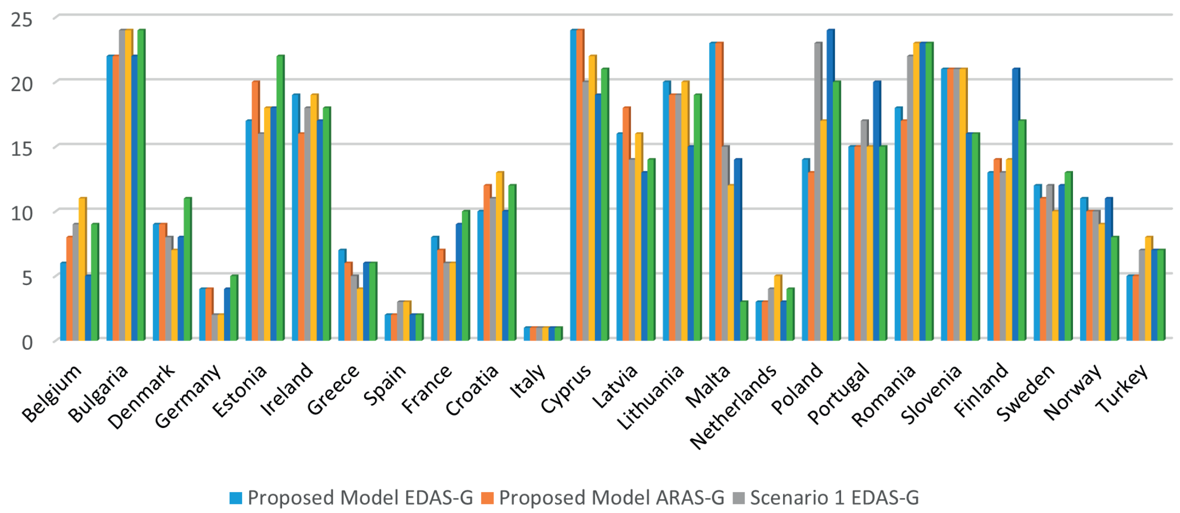

***Figure 2** The line chart of the sensitivity analysis*

strong stability. Cyprus, Malta, Bulgaria, Lithuania, and Slovenia remained in the bottom segment in both scenarios, confirming that the model's outputs do not fluctuate significantly with changes in the criteria weights. Figure 2 presents the line chart of the sensitivity analysis, clearly illustrating the stability of country rankings across the different weighting scenarios.

Overall, the sensitivity analysis demonstrates that the proposed Fuzzy AHP-based EDAS-G and ARAS-G model is robust and reliable. The rankings are not substantially affected by modifications in the weighting structure, indicating that the evaluation framework provides consistent and credible assessments of EU countries' port performance.

6 Discussion

In this section are summarised the elements discussed in previous sections and presents the framework of the key findings obtained from MCDM analyses. The article aim was to provide a systematic comparison of EU countries' port performance using selected criteria, creating a readily accessible reference for further scientific study.

6.1 Research design and findings

Ports are essential components of international trade networks, and their performance has significant implications for the competitiveness and resilience of national and regional economies. The findings of this study provide the new comparative insights into EU port performance by combining the fuzzy and grey-based MCDM approaches. Using expert-derived fuzzy judgments, the criterion weights obtained through the Fuzzy AHP highlight the relative influence of operational, economic, and environmental factors on port performance. The subsequent EDAS-G and ARAS-G analyses reveal consistent country rankings, offering a more nuanced interpretation of performance differences across the EU.

The results indicate that the proposed hybrid model can effectively differentiate between the higher and lower-performing ports, addressing the need for broader comparative assessments identified in the literature. Unlike the majority of existing studies-which typically focus on individual ports-this research provides a multi-country, multi-criteria perspective. This broader analytical scope contributes to a more comprehensive understanding of regional performance patterns and highlights areas where ports underperform relative to their peers.

Moreover, the sensitivity analysis confirms that the rankings remain largely stable under varying weight scenarios, underscoring the robustness of the model. These findings reinforce the value of holistic decision-making tools in port performance evaluation and support their wider adoption in both academic research and strategic industry applications.

The results of the hybrid MCDM analysis reveal that the "Cargo Type" (29%) is the most influential criterion affecting port performance. This indicates that the composition and diversity of cargo handled, such as bulk, liquid, and containerized goods, play a decisive role in shaping operational efficiency and competitiveness. Cargo diversity reflects the adaptability and functional complexity of ports, making it a key determinant of performance.

The second major determinant is the "Cargo Direction" (22%), showing that the balance and volume of inbound and outbound cargo movements are critical for assessing the strategic relevance and throughput efficiency of ports. Closely following, "Container Volume" (21%) emerges as another central indicator, highlighting the importance of containerized trade as a core driver of port activity in the EU.

"Number of Ship Arrivals and Departures" (18%) contributes substantially as well, emphasizing that the frequency of vessel calls remains a significant indicator of operational intensity and port utilization.

In contrast, several indicators have minimal or no impact on overall performance. Passenger Traffic, Air Pollutants, and Municipal Waste Management have weights of 0, suggesting that these variables do not meaningfully differentiate port performance within the EU context. GDP (6%) and Share of Renewable Energy (3%) carry relatively small weights, indicating that broader macroeconomic or sustainability-related factors play a limited role in shaping port efficiency compared to operational cargo-handling attributes.

Overall, the findings underscore that the EU ports are primarily evaluated based on their operational capacity, particularly their ability to handle diverse cargo types, maintain balanced cargo flows, and manage container volumes efficiently. These insights highlight the need for ports to strengthen the cargo-handling infrastructure, diversify operational capabilities, and optimize throughput to maintain and enhance their strategic position within the global supply chains.

6.2 Countries

The results of the EDAS-G and ARAS-G analyses suggest that Italy is the best performer. A review of the literature confirms that various academic studies support this finding. For example, Ruocco and Mazzarino (2026) investigated innovation in the Italian port sector and proposed strategies to improve port performance [54]. Barbagallo et al. (2026), on the other hand, examined ports from a sustainability perspective [55]. Thirdly, de Luca and Valentinuz (2024) assessed social sustainability [56]. These examples demonstrate that academic publications on the Italian port sector corroborate and lay the groundwork for the current findings.

Lupi et al. (2021) argued that Italian ports are well-positioned in terms of cost for cargo originating in North America and the Far East. They also stated that unloading Far Eastern cargo at Italian ports would provide additional benefits for many European countries. Together, these factors make Italian ports strategically important for Europe and could contribute to the development of the Italian port sector [57]. In a separate study, Danielis and Gregori (2013) examined Italian ports and found that they had advantages over Belgian ports [58]. Although the ports compared in this study are limited, the results obtained are consistent with those of the present study for both countries.

Pascual (2016) emphasises that Italy and Spain have a long history of maritime trade. This study shows that these two countries rank first and second, respectively, in terms of port performance. Just as geographical location can, a historical background in ports can give countries an advantage. Similarly, the Netherlands is renowned for its extensive maritime history and favourable geographical location for maritime activities. However, historical processes and geographical location alone are insufficient to determine a country's port performance [59]. As Caballini and Benzi (2023) stated, the efficiency of port processes is paramount. Reducing costs and expediting procedures, particularly customs clearance, are fundamental to overall performance. In this regard, countries would benefit from adopting a holistic approach to port operations and improving all stages of foreign trade [60]. Similarly, Belcore et al. (2024) emphasised the importance of speed in port processes [61].

As shown here, port performance can be evaluated from multiple perspectives. In this context, the countries in question were in this study examined using various criteria, thereby making a valuable addition to the existing body of literature on the subject. However, the evaluation is limited to data from accessible countries. Countries for which data could not be accessed, along with the relevant criteria, were excluded.

7 Conclusion

This study fills a gap in existing literature by evaluating the port performance of EU countries using an integrated approach based on fuzzy and grey logic. The fuzzy AHP was employed to determine the weights of the criteria, and the EDAS-G and ARAS-G method was used for the analysis. The results revealed that container volume and cargo diversity are particularly important performance factors. Italy, Spain, and the Netherlands stand out thanks to their strong infrastructure and high transaction volumes, whereas Malta, Bulgaria, and Cyprus could improve their capacity and efficiency. Furthermore, the sensitivity analysis results confirm that the method provides stable and reliable rankings. Overall, in the study is clearly demonstrated that EU ports must increase their container-handling capacities, adapt to cargo diversity, and improve operational efficiency if they are to remain competitive. In this respect, this research should serve as a strategic guide for policymakers and industry stakeholders alike.

7.1 Policy recommendations

Based on the findings of this study, several strategic recommendations can be made for business leaders and policymakers. Countries like Italy, Spain, and the Netherlands, which rank among the top in port performance, should continue investing in infrastructure to strengthen their role as regional logistics hubs. Businesses operating in these countries can leverage port efficiency to create more flexible and cost-effective supply chains. Policymakers should capitalize on this advantage by promoting green port technologies, digitalization, and sustainable infrastructure development. In contrast, countries, such as Malta, Bulgaria, and Cyprus, which rank lower, should prioritize modernizing their ports' infrastructure, increasing capacity, and attracting private sector investment. Transforming those ports into integrated logistics hubs can significantly increase their competitiveness and enable them to play a more active role in regional trade.

Furthermore, the port performance is influenced not only by physical capacity but by customs procedures, digital integration, and management efficiency, as well. Therefore, strengthening public-private partnerships and establishing transparent, data-driven decision-making processes in port governance are crucial. As a general recommendation for all the countries, regular monitoring of performance metrics and conducting benchmarking can provide a solid foundation for evidence-based policy development. Through such strategic initiatives, ports across Europe can transform from mere transit points into vital economic factors that contribute significantly to regional growth and global trade competitiveness.

7.2 Limitations of the study

From a country perspective, the study's focus on EU countries means global comparisons and comparisons of the performance dynamics of major non-European ports are not possible. Furthermore, the natural geographic and operational differences between island and continental countries, or between Mediterranean and Northern European ports, can structurally affect comparative analyses.

One of the main limitations of this study is its reliance on Eurostat data alone. Another significant limitation is that the analysis only included countries for which the data were available. From a methodological perspective, the assessment was based on expert judgements, and it was found that the ranking results were sensitive to the weighting of the criteria. Therefore, the two different methods were employed and a sensitivity analysis was performed.

7.3 Future research

Given limitations, it is recommended that the future studies comparatively use different fuzzy and grey-based MCDM methods and adopt multi-layered analysis approach that reduces the assessment to port and terminal levels. Adding new criteria to the analysis would broaden the scope of performance measurement. Significant contributions to literature could also be made by conducting the global comparisons that include major non-European trading ports, and by applying scenario analyses to examine the port performance in the context of economic shocks, supply chain crises, and geopolitical developments. Integrating MCDM methods with time series models or machine learning techniques would also be beneficial. It is believed that more comprehensive, multidimensional approaches developed in this direction would enable the port performance to be evaluated more comprehensively from academic and sectoral perspectives.

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Conflicts of 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.

Author Contributions

The first author was responsible for conducting the analyses, developing the overall framework of the paper, supervising the writing process, and performing the final proofreading. The second author contributed by writing the introduction, literature review, and conclusion sections, and assisted in shaping the overall structure of the manuscript. Both authors reviewed and approved the final version of the manuscript.

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