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RESEARCH ARTICLE

A picture fuzzy sets-based decision support model for the holistic assessment of cruise port tourism performance

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ABSTRACT

Sustainable tourism performance of cruise ports is a critical determinant of the long-term competitiveness of both ports and destination regions. This study aims to develop and apply a novel picture fuzzy sets (PFSs)-based decision-support system to systematically evaluate cruise ports' sustainable tourism performance by integrating qualitative expert judgments with quantitative operational data. The proposed framework adopts a multi-attribute group decision-making structure, in which PFSs are employed to explicitly capture uncertainty, hesitation, and neutrality in expert evaluations. Criteria weights are determined using an extended PFS-based weights by envelope and slope (WENSLO) method, while cruise port rankings are obtained through a PFS-integrated multi-attributive border approximation area comparison (MABAC) approach. The applicability of the proposed PFS–WENSLO–MABAC hybrid model is demonstrated through a case study of major cruise ports in Türkiye. The results indicate that the number of cruise passengers (0.5601) and the number of cruise ships (0.4218) are the most influential determinants of sustainable tourism performance, with Kuşadası Cruise Port (0.9029) achieving the highest overall ranking. Sensitivity and robustness analyses confirm the stability of the ranking outcomes under varying weighting scenarios. The findings provide actionable insights for port authorities and policymakers by identifying priority performance dimensions and offering a reliable analytical tool to support strategic planning and sustainability-oriented decision-making in cruise tourism.

1. Introduction

In the realm of marine tourism, cruise ports play a pivotal role by providing essential services to cruise ships and offering a range of amenities to tourists.[1,2] Designed to facilitate the docking of cruise vessels and ensure the safe embarkation and disembarkation of passengers, cruise ports serve as vital gateways to tourist destinations.[3,4] Strategically located near major tourism regions, these ports integrate tourist attractions with the arrival of cruise travelers, thereby enhancing accessibility and connectivity.[5,6] Beyond providing the necessary infrastructure for cruise operations, they also offer facilities that enable tourists to reach destinations efficiently.[7] Consequently, cruise ports contribute directly to the tourism sector, supporting national economic growth at the macro level while fostering regional economic development at the local scale.[8]

As transportation hubs, cruise ports are equipped with berthing facilities, passenger terminals for efficient passenger flow, and security systems to ensure safe operations and passenger processing.[9,10] Moreover, they provide wayfinding and landside transport facilitation, along with facilities for shopping and entertainment.[11] The significance of cruise ports extends beyond economic contributions, encompassing regional development, international visibility, and the creation of employment opportunities.[12] They play a crucial role in advancing tourism infrastructure and fostering seamless connections between destinations and tourists.[13] From a sustainability perspective, cruise ports are central to promoting sustainable tourism,[14] necessitating the effective implementation of environmental management practices and the integration of green technologies.[15] Hence, evaluating the sustainable tourism performance of cruise ports is of critical importance.

While existing literature has extensively examined performance evaluation in cruise ports,[16,17] comparatively limited scholarly attention has been devoted to the systematic assessment of their sustainable tourism performance. To address this gap, this study proposes a novel decision support system for comprehensively evaluating sustainable tourism performance in cruise ports. This study aims to make a methodological contribution to the analysis of cruise port performance levels using both quantitative and qualitative parameters, with an application demonstrated in Türkiye. Türkiye was chosen as the case study due to its relatively high number of cruise ports and its inclusion in major cruise routes. The objective of this research is to provide guidance for decision-makers in cruise port performance analysis by introducing a robust performance analysis-based approach. The proposed approach employs decision models and fuzzy-based cluster decision support techniques, integrating both qualitative and quantitative criteria. Expert opinions are incorporated to strengthen the decision-making process.[18,19] A multi-attribute group decision-making framework is adopted due to its alignment with expert-based evaluation.[20–22] Accordingly, the framework could serve as a robust and systematic decision support tool that guides decision-makers in the comprehensive evaluation of cruise ports with respect to sustainable tourism performance. In this context, the study seeks to address the following research questions:

(i) How can qualitative and quantitative criteria be effectively integrated to assess the sustainable tourism performance of cruise ports?
(ii) How can expert-based multi-attribute decision-making approaches enhance the reliability of performance evaluation?

To address these research questions, a proposed decision support model is developed in this study. Specifically, picture fuzzy sets (PFSs) are utilized to capture expert judgments regarding the importance of performance criteria.[23,24] The weights by envelope and slope (WENSLO) method[25] is applied to determine criterion weights based on the envelope–slope ratio, while the multi-attributive border approximation area comparison (MABAC) method[26] is employed for ranking port performance. WENSLO was chosen because it enables the derivation of a criterion weight matrix based on the class interval matrix and criterion slope vector, ensuring more robust and reliable criterion weights. MABAC was preferred due to its ability to rank alternatives based on the boundary approximation area, providing an effective mechanism for comparative evaluation. By integrating PFS with WENSLO and MABAC, the study introduces the hybrid PFS–WENSLO–MABAC model, which enables the linguistic evaluation of qualitative criteria in both criterion weighting and alternative ranking.

The proposed PFS–WENSLO–MABAC framework goes beyond a straightforward integration of existing methods by introducing a novel hybrid decision-making structure that systematically embeds PFS theory into both the criterion weighting and alternative ranking stages. Specifically, the framework extends the WENSLO weighting mechanism and the MABAC ranking procedure into a picture fuzzy environment, enabling the simultaneous handling of qualitative and quantitative criteria under uncertainty, hesitation, and partial information. This integration is supported by a unified mathematical formulation and a structured algorithmic workflow, which enhances robustness, sensitivity, and interpretability in evaluating cruise port performance. As a result, the proposed model constitutes a methodological advancement rather than a simple aggregation of existing approaches. The key contributions of this research are as follows:

(i) Introduction of the PFS–WENSLO–MABAC model, integrating qualitative and quantitative criteria to comprehensively evaluate cruise port performance.
(ii) Development of a multi-attribute group decision-making-based framework for systematic performance evaluation.
(iii) Enhancement of PFS–WENSLO for criterion weighting and application of PFS–MABAC for nuanced performance ranking.
(iv) Provision of a structured algorithm outlining the step-by-step application of the hybrid model.
(v) Application of the model to cruise ports in Türkiye, confirming its practicality and effectiveness.
(vi) Establishment of a robust decision support system for assessing cruise terminal performance on a macro scale.
(vii) Provision of strategic insights for cruise terminal managers and policymakers to support informed decision-making and resource allocation.
(viii) Contribution of findings to cruise route planners, offering valuable input for optimizing itineraries and enhancing the cruise tourism experience.

This paper is structured into six sections. **Section 2** reviews the literature. **Section 3** details the proposed PFS–WENSLO–MABAC methodology. **Section 4** presents the Türkiye case study. **Section 5** reports results and managerial implications. **Section 6** concludes with a discussion of limitations and recommendations for future research.

2. Literature review

This study employs PFS–WENSLO–MABAC for evaluating cruise port performance. To contextualize this approach, the literature review is organized into three main stages: (i) research on the application of WENSLO or criteria weighting, (ii) studies employing MABAC for alternative ranking, and (iii) research focusing on port selection.

Recent literature highlights the growing use of WENSLO as a robust criteria weighting technique across diverse decision-making contexts. For instance, Gopisetty and Sama[27] introduced the double normalization WENSLO method, demonstrating its effectiveness in evaluating socio-economic performance across countries. Subramanian et al.[28] integrated WENSLO with a decision tree algorithm for healthcare supplier selection, offering a novel machine learning-based multi-criteria decision-making (MCDM) approach. Kahreman[29] applied WENSLO to assess the productive capacity performance of E7 countries, combined with the alternative ranking technique based on adaptive standardized intervals (ARTASI) for ranking. Similarly, Pamucar et al.[30] developed a WENSLO–ARTASI framework to determine airport efficiency, revealing varying priorities across different airport categories. Finally, Kara et al.[31] employed WENSLO with PFS to support an artificial intelligence-based sustainable logo design, ensuring expert-driven and robust selection outcomes. These studies collectively underscore WENSLO's effectiveness in providing objective and reliable criterion weighting for complex MCDM problems.

The MABAC method has also been widely applied in recent research as an alternative ranking method. Jafari and Naghdi Khanachah[32] proposed a multi-normalization-based MABAC to evaluate supplier resilience under uncertainty using Pythagorean fuzzy sets. Kizielewicz et al.[33] presented fuzzy normalization-based MABAC to minimize ranking reversals in e-commerce decision-making. Naz et al.[34] enhanced MABAC with 2-tuple linguistic rung PFSs and power-weighted aggregation operators for selecting secure blockchain systems. Fan et al.[35] introduced the PFS–method based on the removal effects of criteria–cumulative prospect theory–MABAC framework to evaluate wearable health technology devices while integrating objectivity, subjectivity, and expert psychological behavior. Bi et al.[36] applied MABAC to prioritize electric vehicle charging station locations in Beijing, whereas Debnath et al.[37] utilized the q-rung orthopair–stepwise weight assessment ratio analysis–MABAC framework for assessing high-speed rail corridors in India. Soni et al.[38] integrated MABAC with q-rung orthopair fuzzy numbers for selecting optimal sustainable polymeric composites. Gao et al.[39] employed MABAC within an intuitionistic fuzzy set framework to rank geothermal site alternatives, and Ali and Yang[40] demonstrated its application with circular spherical fuzzy 2-tuple linguistic sets for multi-attribute decision-making. Collectively, these studies illustrate MABAC's versatility and reliability in ranking alternatives across diverse fuzzy and uncertain decision-making environments.

Moreover, several studies in the literature have focused on the application of PFSs. Senapati and Chen[41] proposed a weighted aggregated sum product assessment-based outranking approach within a PFS framework, enabling the effective handling of uncertainty and hesitation inherent in MCDM problems. Hussain et al.[42] developed aggregation methodologies that can more accurately capture the uncertainty, hesitation, and vagueness present in complex multi-attribute group decision-making contexts. Javeed et al.[43] demonstrated that, by explicitly incorporating degrees of acceptance, neutrality, rejection, and refusal, the PFS framework provides a more comprehensive and realistic representation of uncertainty and human judgment compared to traditional fuzzy and intuitionistic fuzzy models. Asif et al.[44] introduced a framework based on Aczel–Alsina intuitionistic fuzzy aggregation operators, which effectively captures uncertainty and human judgment, thereby enabling robust and reliable decision-making in complex real-world problems. Additionally, Saeed et al.[45] proposed a cubic Pythagorean fuzzy soft set framework that integrates interval-valued Pythagorean fuzzy sets and Pythagorean fuzzy sets simultaneously, offering a more comprehensive and flexible representation of uncertainty in decision-making processes.

The third focus of the literature review concerns port selection, a critical decision-making process for shipping lines, port authorities, and policymakers. Feng et al.[46] utilized big data from an automatic identification system to analyze port selection between Shanghai and Ningbo Zhoushan, providing insights into vessel deployment patterns and feeder networks. Pham et al.[47] integrated fuzzy technique for order preference by similarity to ideal solution (TOPSIS), analytic hierarchy process, and cumulative prospect theory to evaluate six container terminals in Vietnam, identifying operational efficiency as the key selection criterion. Pabón-Noguera et al.[48] applied a principal component analysis–TOPSIS hybrid approach to rank container terminals in Latin America and the Caribbean, highlighting factors influencing efficiency and competitiveness. Yeo et al.[49] examined port selection for South Korean firms in Southeast Asia using a fuzzy-analytic hierarchy process–TOPSIS approach, identifying port call frequency, charges, crane capacity, and proximity to routes as significant factors. Patel and Chang[50] combined MABAC with entropy and best-worst methods to develop a multi-criteria Port Competitiveness Index for ranking major Asia–Europe maritime ports. Ibeh[51] evaluated port efficiency and productivity in six West African ports using data envelopment analysis–slack-based measurement and the Malmquist Productivity Index, providing benchmarks for operational and technological improvements. These studies collectively highlight the importance of integrating MCDM methods with empirical and fuzzy data to support strategic port selection and operational planning. A summary of the literature review is presented in **Table 1**.

3. Methodology

In this study, we developed and applied the PFS–WENSLO–MABAC hybrid method to assess cruise ports' sustainable tourism performance. The inclusion of both quantitative and qualitative parameters in cruise port performance evaluation, along with expert assessments based on linguistic and fuzzy logic, underscores the suitability of this hybrid method. This hybrid method incorporated both qualitative and quantitative criteria, experts, and alternatives (i.e., cruise ports) as inputs in the decision model. Outputs included expert-importance weights, the weights of the criteria, and the performance ranking of the alternatives. PFS–WENSLO–MABAC consisted of three main stages. In the first stage, the importance levels of experts were determined using PFSs. In the second stage, the weights of the criteria were calculated using the PFS–WENSLO method. In the third stage, the ranking of the alternatives was established using the PFS–MABAC method. **Figure 1** illustrates the methodology flow. The preliminaries of PFSs are provided in Appendix A.

The PFS–WENSLO–MABAC hybrid model was formulated for assessing sustainable port performance. Consider $X_{\mathfrak{z}} = \{X_1, X_2, \ldots, X_{\mathfrak{Z}}\}$ $(\mathfrak{z} = \overline{1,\ \mathfrak{Z}})$ as the set of alternative cruise ports, $\Psi_{\mathfrak{y}^{(ql)}} = \left\{\Psi_1, \Psi_2, \ldots, \Psi_{\mathfrak{Y}^{(ql)}}\right\}$ $(\mathfrak{y}^{(ql)} = \overline{1, \mathfrak{Y}^{(ql)}})$ as the set of qualitative criteria, and $\Psi_{\mathfrak{y}^{(qn)}} = \left\{\Psi_1, \Psi_2, \ldots, \Psi_{\mathfrak{Y}^{(qn)}}\right\}$ $(\mathfrak{y}^{(qn)} = \overline{1, \mathfrak{Y}^{(qn)}})$ as the set of quantitative criteria. The set $\Omega_{\mathfrak{r}} = \{\Omega_1, \Omega_2, \ldots, \Omega_{\mathfrak{r}}\}$ $\left(\mathfrak{r} = \overline{1, \mathfrak{X}}\right)$ serves as an indicator, reflecting the involvement of experts in a comprehensive evaluation of strategy selection. The notations used in this study are presented in Appendix B. The procedural steps of PFS–

Table 1. Summary of the literature review

Studies	Methodology	Application domain	Main contribution
Gopisetty and Sama[27]	DN–WENSLO	Socio-economic performance evaluation	Proposed Double Normalization WENSLO for cross-country performance assessment
Subramanian et al.[28]	WENSLO + decision tree	Healthcare supplier selection	Integrated machine learning with MCDM for supplier evaluation
Kahreman[29]	WENSLO–ARTASI	E7 country productivity assessment	Evaluated productive capacity performance
Pamucar et al.[30]	WENSLO–ARTASI	Airport efficiency analysis	Identified efficiency priorities across airport categories
Kara et al.[31]	WENSLO + PFS	Artificial intelligence-based sustainable logo design	Developed an expert-driven robust weighting and selection framework
Jafari and Naghdi Khanachah[32]	MULTIMABAC	Supplier resilience evaluation	Addressed uncertainty in resilience assessment
Kizielewicz et al.[33]	FN–MABAC	E-commerce decision-making	Reduced ranking reversals in alternative evaluation
Naz et al.[34]	Power-weighted MABAC	Blockchain system selection	Enhanced security-oriented decision-making
Fan et al.[35]	PFS–MEREC–CPT–MABAC	Wearable health technology evaluation	Integrated objectivity, subjectivity, and behavioral factors
Bi et al.[36]	MABAC	Changing station location	Prioritized charging station locations in Beijing
Debnath et al.[37]	q-ROF–SWARA–MABAC	High-speed rail corridor assessment	Evaluated infrastructure alternatives under uncertainty
Soni et al.[38]	MABAC	Sustainable polymer composite selection	Supported sustainable material selection
Gao et al.[39]	MABAC	Geothermal site selection	Ranked geothermal energy alternatives
Ali and Yang[40]	MABAC	Multi-attribute decision-making	Advanced linguistic-based ranking approach
Senapati and Chen[41]	WASPAS-based outranking	General MCDM problems	Effectively handled uncertainty and hesitation
Hussain et al.[42]	Aggregation operators	MAGDM problems	Captured uncertainty and vagueness in group decisions
Javeed et al.[43]	PFS-based decision framework	Human judgment modeling	Improved realism over fuzzy and intuitionistic fuzzy models
Asif et al.[44]	Aczel–Alsina aggregation	Real-world decision-making	Enhanced robustness and reliability
Saeed et al.[45]	Cubic Pythagorean fuzzy soft set	Medical diagnosis	Provided flexible uncertainty representation
Feng et al.[46]	AIS big data analysis	Port selection	Analyzed vessel deployment and feeder networks
Pham et al.[47]	Fuzzy AHP–TOPSIS–CPT	Container terminal evaluation	Identified efficiency as a key criterion
Pabón-Noguera et al.[48]	PCA–TOPSIS	Port competitiveness	Ranked Latin American container terminals
Yeo et al.[49]	Fuzzy AHP–TOPSIS	Port selection (Southeast Asia)	Identified key port selection factors
Patel and Chang[50]	Entropy–BWM–MABAC	Port competitiveness index	Ranked Asia–Europe maritime ports
Ibeh[51]	DEA–SBM + MPI	Port efficiency analysis	Provided productivity benchmarks

Abbreviations: AHP, Analytic hierarchy process; AIS, Automatic identification system; ARTASI, Alternative ranking technique based on adaptive standardized intervals; CPT, Cumulative prospect theory; DEA, Data envelopment analysis; DN, Double normalization; FN, Fuzzy normalization; MABAC, Multi-attributive border approximation area comparison; MAGDM, Multi-attribute group decision-making; MCDM, Multi-criteria decision-making; MEREC, Method based on the removal effects of criteria; MULTIMABAC, Multi normalization-based multi-attributive border approximation area comparison; PCA, Principal component analysis; PCI: Port Competitiveness Index; PFSs, Picture fuzzy sets; q-ROF, q-Rung orthopair; SBM, Slack-based measurement; SWARA, Stepwise weight assessment ratio analysis; TOPSIS, Technique for order preference by similarity to ideal solution; WASPAS, Weighted aggregated sum product assessment; WENSLO, Weights by envelope and slope.

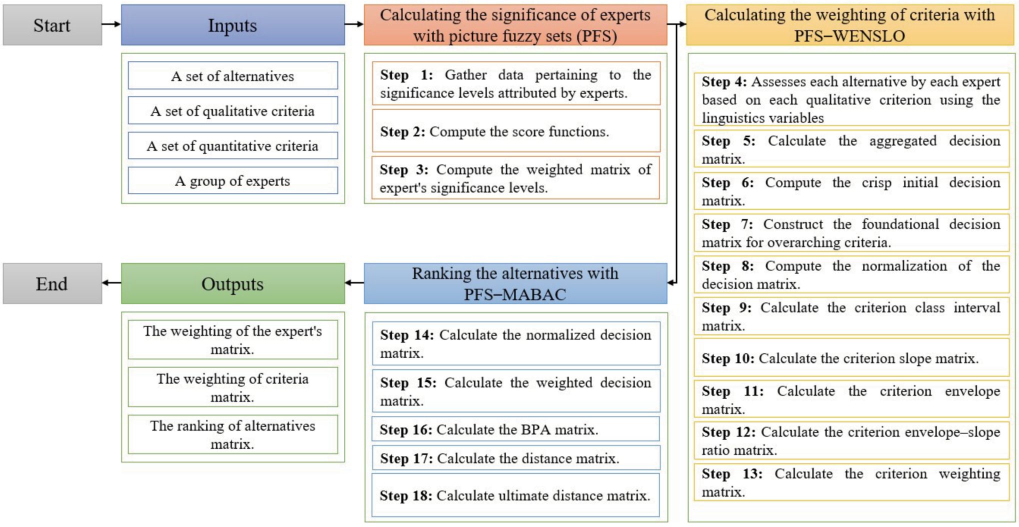

Figure 1. The methodological framework of PFS–WENSLO–MABAC
Abbreviations: BPA: Boundary proximity area; MABAC: Multi-attributive border approximation area comparison; PFS: Picture fuzzy set; WENSLO: Weights by envelope and slope.

WENSLO–MABAC are detailed as follows:

- **First stage**: Determining weights assigned to each expert.
  - **Step 1**: To establish expert weights, the significance of each expert was first determined through linguistic variables (LVs) outlined in **Table 2**.[52] These LVs were then converted into PFSs, forming a decision matrix to ascertain the importance levels of experts.
  - **Step 2:** To assess the significance levels of experts, precise values were computed through the utilization of the score function $\mathcal{S}\left(\widetilde{\Omega}_{\mathfrak{r}}\right)$ as outlined in **Equation** (1) for PFSs:

$$\mathcal{S}\left(\widetilde{\Omega}_{\mathfrak{r}}\right)=\frac{1}{3}\left(\left(\theta_{\widetilde{\Omega}_{\mathfrak{r}}}(\mathfrak{s})\right)+\left(1-\eta_{\widetilde{\Omega}_{\mathfrak{r}}}(\mathfrak{s})\right)+\left(1-\zeta_{\widetilde{\Omega}_{\mathfrak{r}}}(\mathfrak{s})\right)\right);\left(\mathfrak{r}=\overline{1,\ \mathfrak{X}}\right)\times\left|\ \mathcal{S}\left(\widetilde{\Omega}\right)\in[0,1]\right. \quad (1)$$

  - **Step 3:** The weighting matrix generation for the experts $\left(w=[w_{\mathfrak{r}}]_{\mathfrak{X}}\right)$ was performed using **Equation** (2):

$$w_{\mathfrak{r}}=\frac{\mathcal{S}\left(\widetilde{\Omega}_{\mathfrak{r}}\right)}{\sum_{\mathfrak{r}=1}^{\mathfrak{X}}\mathcal{S}\left(\widetilde{\Omega}_{\mathfrak{r}}\right)};\left(\mathfrak{r}=\overline{1,\ \mathfrak{X}}\right) \quad (2)$$

- **Second stage**: Calculating weights assigned to each criterion.
  - **Step 4**: The initial decision matrices $\left(\widetilde{\mathfrak{P}}^{(\widetilde{\Omega}_{\mathfrak{r}})}=\left[\widetilde{\mathfrak{P}}^{(\widetilde{\Omega}_{\mathfrak{r}})}_{\mathfrak{z}\mathfrak{y}^{(ql)}}\right]_{\mathfrak{Z}x\mathfrak{Y}^{(ql)}}\right)$ for the qualitative criteria were derived, where $\widetilde{\mathfrak{P}}^{(\widetilde{\Omega}_{\mathfrak{r}})}_{\mathfrak{z}\mathfrak{y}^{(ql)}}=\left(\theta_{\widetilde{\mathfrak{P}}^{(\widetilde{\Omega}_{\mathfrak{r}})}_{\mathfrak{z}\mathfrak{y}^{(ql)}}}(\mathfrak{s}),\eta_{\widetilde{\mathfrak{P}}^{(\widetilde{\Omega}_{\mathfrak{r}})}_{\mathfrak{z}\mathfrak{y}^{(ql)}}}(\mathfrak{s}),\zeta_{\widetilde{\mathfrak{P}}^{(\widetilde{\Omega}_{\mathfrak{r}})}_{\mathfrak{z}\mathfrak{y}^{(ql)}}}(\mathfrak{s})\right)$ $\left(\mathfrak{z}=\overline{1,\mathfrak{Z}};\ \mathfrak{y}^{(ql)}=\overline{1,\mathfrak{Y}^{(ql)}};\ \mathfrak{r}=\overline{1,\mathfrak{X}}\right)$ represents a PFS utilized for the evaluation of alternative $X_{\mathfrak{z}}$ concerning qualitative criteria $\Psi_{\mathfrak{y}^{(ql)}}$, based on an expert assessment by the invited expert $\Omega_{\mathfrak{r}}$. The initial decision matrices were established using a PFS linguistic scale outlined in **Table 3.**[52]
  - **Step 5:** The picture fuzzy weighted average aggregation operator, as shown in **Equation** (3), was applied to compute the aggregated decision matrix $\left(\widetilde{\mathfrak{P}}=\left[\widetilde{\mathfrak{P}}_{\mathfrak{z}\mathfrak{y}^{(ql)}}\right]_{\mathfrak{Z}x\mathfrak{Y}^{(ql)}}\right)$:

$$PFWA\left(\widetilde{\mathfrak{P}}^{(1)},\widetilde{\mathfrak{P}}^{(2)},\ldots,\widetilde{\mathfrak{P}}^{(\mathfrak{X})}\right)=\oplus_{\mathfrak{r}=1}^{\mathfrak{X}}w_{\mathfrak{r}}\widetilde{\mathfrak{P}}^{(\mathfrak{r})}$$
$$=\left\{\left(\begin{array}{c}\left(1-\prod_{\mathfrak{r}=1}^{\mathfrak{X}}\left(1-\theta_{\widetilde{\mathfrak{P}}^{(\mathfrak{r})}}(\mathfrak{s})\right)^{w_{\mathfrak{r}}}\right),\\ \left(\prod_{\mathfrak{r}=1}^{\mathfrak{X}}\left(\eta_{\widetilde{\mathfrak{P}}^{(\mathfrak{r})}}(\mathfrak{s})\right)^{w_{\mathfrak{r}}}\right),\\ \left(\prod_{\mathfrak{r}=1}^{\mathfrak{X}}\left(\zeta_{\widetilde{\mathfrak{P}}^{(\mathfrak{r})}}(\mathfrak{s})\right)^{w_{\mathfrak{r}}}\right)\end{array}\right)\ \middle|\ \mathfrak{s}\in\mathfrak{S}\right\} \quad (3)$$

Table 2. Linguistic variables utilized by experts to evaluate expert importance[52]

Linguistic variables	Picture fuzzy sets
Very important (VI)	(0.700, 0.010, 0.010)
Important (I)	(0.600, 0.035, 0.030)
Medium important (MI)	(0.260, 0.260, 0.260)
Unimportant (UI)	(0.210, 0.270, 0.325)
Very unimportant (VUI)	(0.015, 0.397, 0.397)

Table 3. Linguistic variables for the alternative evaluation concerning the criteria

Linguistic variables	**Picture fuzzy sets**
Extremely good (EG)	(0.995, 0.000, 0.000)
Very very good (VVG)	(0.825, 0.015, 0.015)
Very good (VG)	(0.755, 0.043, 0.050)
Good (G)	(0.650, 0.131, 0.137)
Medium good (MG)	(0.510, 0.135, 0.250)
Medium (M)	(0.260, 0.260, 0.260)
Medium bad (MB)	(0.225, 0.390, 0.263)
Bad (B)	(0.150, 0.400, 0.295)
Very bad (VB)	(0.060, 0.410, 0.400)
Very very bad (VVB)	(0.040, 0.400, 0.400)

with $w = (w_1, w_2, \ldots, w_{\mathfrak{x}}, \ldots, w_{\mathfrak{X}})$ for $w_{\mathfrak{x}} \in [0,1]$ $(\mathfrak{x} = \overline{1,\mathfrak{X}})$ with the constraint $\sum_{\mathfrak{x}=1}^{\mathfrak{X}} w_{\mathfrak{x}} = 1$.

- **Step 6**: The crisp initial decision matrix for qualitative criteria $\left(\mathfrak{P} = \left[\mathfrak{P}_{\mathfrak{z}\mathfrak{y}^{(ql)}}\right]_{\mathfrak{Z}x\mathfrak{Y}^{(ql)}}\right)$ was computed using the score function $\left(\mathcal{S}\left(\widetilde{\mathfrak{P}}_{\mathfrak{z}\mathfrak{y}^{(ql)}}\right)\right)$ described in **Equation** (4):

$$\mathcal{S}\left(\widetilde{\mathfrak{P}}_{\mathfrak{z}\mathfrak{y}^{(ql)}}\right) = \frac{1}{3}\left(\left(\theta_{\widetilde{\mathfrak{P}}_{\mathfrak{z}\mathfrak{y}^{(ql)}}}(\mathfrak{s})\right) + \left(1 - \eta_{\widetilde{\mathfrak{P}}_{\mathfrak{z}\mathfrak{y}^{(ql)}}}(\mathfrak{s})\right) + \left(1 - \zeta_{\widetilde{\mathfrak{P}}_{\mathfrak{z}\mathfrak{y}^{(ql)}}}(\mathfrak{s})\right)\right); \left(\mathfrak{z} = \overline{1,\mathfrak{Z}};\ \mathfrak{y}^{(ql)} = \overline{1,\mathfrak{Y}^{(ql)}}\right) \quad (4)$$

with $\mathcal{S}\left(\widetilde{\mathfrak{P}}_{\mathfrak{z}\mathfrak{y}^{(ql)}}\right) \in [0,1]$ and $\mathcal{S}\left(\widetilde{\mathfrak{P}}_{\mathfrak{z}\mathfrak{y}^{(ql)}}\right) = \mathfrak{P}_{\mathfrak{z}\mathfrak{y}^{(ql)}}$.

- **Step 7**: The foundational decision matrix for overarching criteria $\left(\mathfrak{K} = [\mathfrak{K}_{\mathfrak{z}\mathfrak{y}}]_{\mathfrak{Z}x\mathfrak{Y}}\right)$ was formulated through the integration of both the definitive initial decision matrix addressing qualitative criteria $\left(\mathfrak{P} = \left[\mathfrak{P}_{\mathfrak{z}\mathfrak{y}^{(ql)}}\right]_{\mathfrak{Z}x\mathfrak{Y}^{(ql)}}\right)$ and the initial decision matrix concerning quantitative criteria $\left(\mathfrak{L} = \left[\mathfrak{L}_{\mathfrak{z}\mathfrak{y}^{(qn)}}\right]_{\mathfrak{Z}x\mathfrak{Y}^{(qn)}}\right)$.
- **Step 8**: The normalization of the decision matrix $\left(\mathfrak{N} = [\mathfrak{N}_{\mathfrak{z}\mathfrak{y}}]_{\mathfrak{Z}x\mathfrak{Y}}\right)$ was computed using **Equation** (5). In this step, a linear normalization approach was applied as:

$$\mathfrak{N}_{\mathfrak{z}\mathfrak{y}} = \frac{\mathfrak{K}_{\mathfrak{z}\mathfrak{y}}}{\sum_{l=1}^{\mathfrak{Z}} \mathfrak{K}_{l\mathfrak{y}}}; \left(\mathfrak{z} = \overline{1,\mathfrak{Z}};\ \mathfrak{y} = \overline{1,\mathfrak{Y}}\right) \quad (5)$$

- **Step 9**: **Equation** (6) was applied (i.e., Sturges' rule) to calculate the criterion class interval matrix $\left(\Delta\mathfrak{N}_{\mathfrak{y}} = [\Delta\mathfrak{N}_{\mathfrak{y}}]_{\mathfrak{Y}}\right)$:

$$\Delta\mathfrak{N}_{\mathfrak{y}} = \frac{max_{\mathfrak{z}=1,2,..,\mathfrak{Z}}\left(\mathfrak{N}_{\mathfrak{z}\mathfrak{y}}\right) - min_{\mathfrak{z}=1,2,..,\mathfrak{Z}}\left(\mathfrak{N}_{\mathfrak{z}\mathfrak{y}}\right)}{1 + 3.322\log\left(\mathfrak{Z}\right)}; \left(\mathfrak{y} = \overline{1,\mathfrak{Y}}\right) \quad (6)$$

- **Step 10**: **Equation** (7) was applied to calculate the criterion slope matrix $\left(\tan\sigma_{\mathfrak{y}} = [tan\sigma_{\mathfrak{y}}]_{\mathfrak{Y}}\right)$:

$$tan\sigma_{\mathfrak{y}} = \frac{\sum_{\mathfrak{z}=1}^{\mathfrak{Z}} \mathfrak{N}_{\mathfrak{z}\mathfrak{y}}}{(\mathfrak{Z} - 1)\left(\Delta\mathfrak{N}_{\mathfrak{y}}\right)}; \left(\mathfrak{y} = \overline{1,\mathfrak{Y}}\right) \quad (7)$$

- **Step 11**: **Equation** (8) was applied to calculate the criterion envelope matrix $\left(E_{\mathfrak{y}} = [E_{\mathfrak{y}}]_{\mathfrak{Y}}\right)$:

$$E_{\mathfrak{y}} = \sum_{\mathfrak{z}=1}^{\mathfrak{Z}-1} \sqrt{(\mathfrak{N}_{\mathfrak{z}+1,\mathfrak{y}} - \mathfrak{N}_{\mathfrak{z}\mathfrak{y}})^2 + (\Delta\mathfrak{N}_{\mathfrak{y}})^2}; \left(\mathfrak{y} = \overline{1,\mathfrak{Y}}\right) \quad (8)$$

- **Step 12**: **Equation** (9) was applied to calculate the criterion envelope–slope ratio matrix $\left(ES_{\mathfrak{y}} = [ES_{\mathfrak{y}}]_{\mathfrak{Y}}\right)$:

$$ES_{\mathfrak{y}} = \frac{E_{\mathfrak{y}}}{tan\sigma_{\mathfrak{y}}}; \left(\mathfrak{y} = \overline{1,\mathfrak{Y}}\right) \quad (9)$$

- **Step 13**: **Equation** (10) was applied to calculate the criterion weighting matrix $\left(\mathbb{W}_{\mathfrak{y}} = [\mathbb{W}_{\mathfrak{y}}]_{\mathfrak{Y}}\right)$:

$$\mathbb{W}_{\mathfrak{y}} = \frac{ES_{\mathfrak{y}}}{\sum_{h=1}^{\mathfrak{Y}} ES_h}; \left(\mathfrak{y} = \overline{1,\mathfrak{Y}}\right) \quad (10)$$

- **Third stage**: Determining rankings of the alternatives.
  - **Step 14**: The decision matrix $\left(\mathfrak{K} = [\mathfrak{K}_{\mathfrak{z}\mathfrak{y}}]_{\mathfrak{Z}x\mathfrak{Y}}\right)$ obtained in Step 7 was considered the initial for the alternative ranking process. This decision matrix underwent the linear normalization process outlined in **Equation** (11), resulting in the normalized decision matrix $\left(\mathfrak{J} = [\mathfrak{J}_{\mathfrak{z}\mathfrak{y}}]_{\mathfrak{Z}x\mathfrak{Y}}\right)$ for the purpose of alternative prioritization:

$$\mathfrak{J}_{\mathfrak{z}\mathfrak{y}} = \begin{cases} \dfrac{\mathfrak{K}_{\mathfrak{z}\mathfrak{y}} - min_{\mathfrak{z}=1,2,..,\mathfrak{Z}}\left(\mathfrak{K}_{\mathfrak{z}\mathfrak{y}}\right)}{max_{\mathfrak{z}=1,2,..,\mathfrak{Z}}\left(\mathfrak{K}_{\mathfrak{z}\mathfrak{y}}\right) - min_{\mathfrak{z}=1,2,..,\mathfrak{Z}}\left(\mathfrak{K}_{\mathfrak{z}\mathfrak{y}}\right)}; \\ \text{for benefit criteria} \\ \dfrac{\mathfrak{K}_{\mathfrak{z}\mathfrak{y}} - max_{\mathfrak{z}=1,2,..,\mathfrak{Z}}\left(\mathfrak{K}_{\mathfrak{z}\mathfrak{y}}\right)}{min_{\mathfrak{z}=1,2,..,\mathfrak{Z}}\left(\mathfrak{K}_{\mathfrak{z}\mathfrak{y}}\right) - max_{\mathfrak{z}=1,2,..,\mathfrak{Z}}\left(\mathfrak{K}_{\mathfrak{z}\mathfrak{y}}\right)}; \\ \text{for cost criteria} \end{cases}; \left(\mathfrak{z} = \overline{1,\mathfrak{Z}};\ \mathfrak{y} = \overline{1,\mathfrak{Y}}\right) \quad (11)$$

  - **Step 15**: In this step, the decision matrix was weighted, considering the levels of importance assigned to the criteria, to prepare for the subsequent phase. The weighted decision matrix $\left(\mathfrak{H} = [\mathfrak{H}_{\mathfrak{z}\mathfrak{y}}]_{3x\mathfrak{Y}}\right)$ was calculated using **Equation** (12):

$$\mathfrak{H}_{\mathfrak{z}\mathfrak{y}} = \mathbb{W}_{\mathfrak{y}} \left(\mathfrak{I}_{\mathfrak{z}\mathfrak{y}} + 1\right); \left(\mathfrak{z} = \overline{1,3};\ \mathfrak{y} = \overline{1,\mathfrak{Y}}\right) \quad (12)$$

- **Step 16**: The boundary proximity area (BPA) matrix $\left(\mathfrak{F} = [\mathfrak{F}_{\mathfrak{z}}]_3\right)$ was computed as **Equation** (13):

$$\mathfrak{F}_{\mathfrak{z}} = \left(\prod_{\mathfrak{y}=1}^{\mathfrak{Y}} \mathfrak{H}_{\mathfrak{z}\mathfrak{y}}\right)^{1/\mathfrak{Y}}; \left(\mathfrak{z} = \overline{1,3}\right) \quad (13)$$

- **Step 17**: The distance matrix of alternatives $\left(\mathfrak{E} = [\mathfrak{E}_{\mathfrak{z}\mathfrak{y}}]_{3x\mathfrak{Y}}\right)$ to BPA was generated as **Equation** (14):

$$\mathfrak{E}_{\mathfrak{z}\mathfrak{y}} = \mathfrak{H}_{\mathfrak{z}\mathfrak{y}} - \mathfrak{F}_{\mathfrak{z}}; \left(\mathfrak{z} = \overline{1,3};\ \mathfrak{y} = \overline{1,\mathfrak{Y}}\right) \quad (14)$$

- **Step 18**: The ultimate distance matrix $\left(\mathfrak{D} = [\mathfrak{D}_{\mathfrak{z}}]_3\right)$ of the alternatives from BPA was computed using **Equation** (15):

$$\mathfrak{D}_{\mathfrak{z}} = \sum_{\mathfrak{y}=1}^{\mathfrak{Y}} \mathfrak{E}_{\mathfrak{z}\mathfrak{y}}; \left(\mathfrak{z} = \overline{1,3}\right) \quad (15)$$

where an alternative with the highest value is identified as the prime choice. The algorithm for PFS–WENSLO–MABAC is depicted in Appendix C and shown in **Figure 2**.

4. Case study

This research, which focuses on determining the sustainable tourism performance of cruise ports, proposes a hybrid method named PFS–WENSLO–MABAC. To support the applicability of the approach, a case study was conducted concerning the sustainable tourism performance of cruise ports in Türkiye. The case study had two primary objectives. The first objective was to test the applicability and robustness of PFS–WENSLO–MABAC. The second objective was to gain managerial insights by evaluating the sustainable tourism performance of cruise ports in Türkiye using real data. In this context, three key aspects were identified for creating the case study. The first aspect involved identifying sustainable tourism criteria, encompassing both qualitative and quantitative dimensions. The second aspect was to provide information about cruise ports in Türkiye. The third aspect was to determine the expert group for evaluating cruise ports in Türkiye and gather their opinions. Subsequently, detailed information about the expert group, criteria, and cruise ports in Türkiye is presented in the following subsections.

4.1. Experts, criteria, and cruise ports

4.1.1. Identification of experts

In this case study, the sustainable tourism performance of cruise ports in Türkiye was brought into focus in relation to tourism and sustainability. The primary objective was to establish an assessment system for cruise ports that incorporates various qualitative criteria, beyond just the number of tourists and cruise ships. This systematic framework is presented in the algorithm. The accurate determination of inputs is crucial for the algorithm to function properly. The selection of the expert group among the inputs is also crucial for obtaining accurate and robust results. Therefore, a meticulous approach was taken in determining the expert group. The most crucial parameter considered in this process was ensuring that the members of the expert group had knowledge about the cruise ports under evaluation and the competence to assess these ports based on qualitative criteria.

The expert group consisted of one chief port officer, two operations/cruise terminal managers, two operations directors, two terminal managers, and one operations director. Through discussions with this expert group, both the effectiveness levels of the experts in the decision-making process and the evaluation of cruise ports based on qualitative criteria were determined. Information regarding the expert group is presented in **Table 4**. Additionally, the importance levels of the experts were also indicated.

4.1.2. Identification of criteria

In the case study developed to assess the sustainable tourism performance of cruise ports in terms of tourism, nine criteria were identified. The initial seven criteria are qualitative, while the final two are quantitative. Detailed explanations for each criterion are as follows:

(i) Port infrastructure ($\Psi_{1(ql)}$): In evaluating cruise port performance, port infrastructure is a critical criterion, encompassing the physical attributes, facilities, and structural capacity required to accommodate cruise tourism effectively. This assessment emphasizes berth capacity, safe berth depth, navigational channels, loading/unloading equipment, and land connectivity, highlighting the infrastructure's essential role in facilitating efficient passenger embarkation, disembarkation, and overall port operations.[53,54]

(ii) Safety and security ($\Psi_{2(ql)}$): Safety and security constitute a critical dimension in evalu-

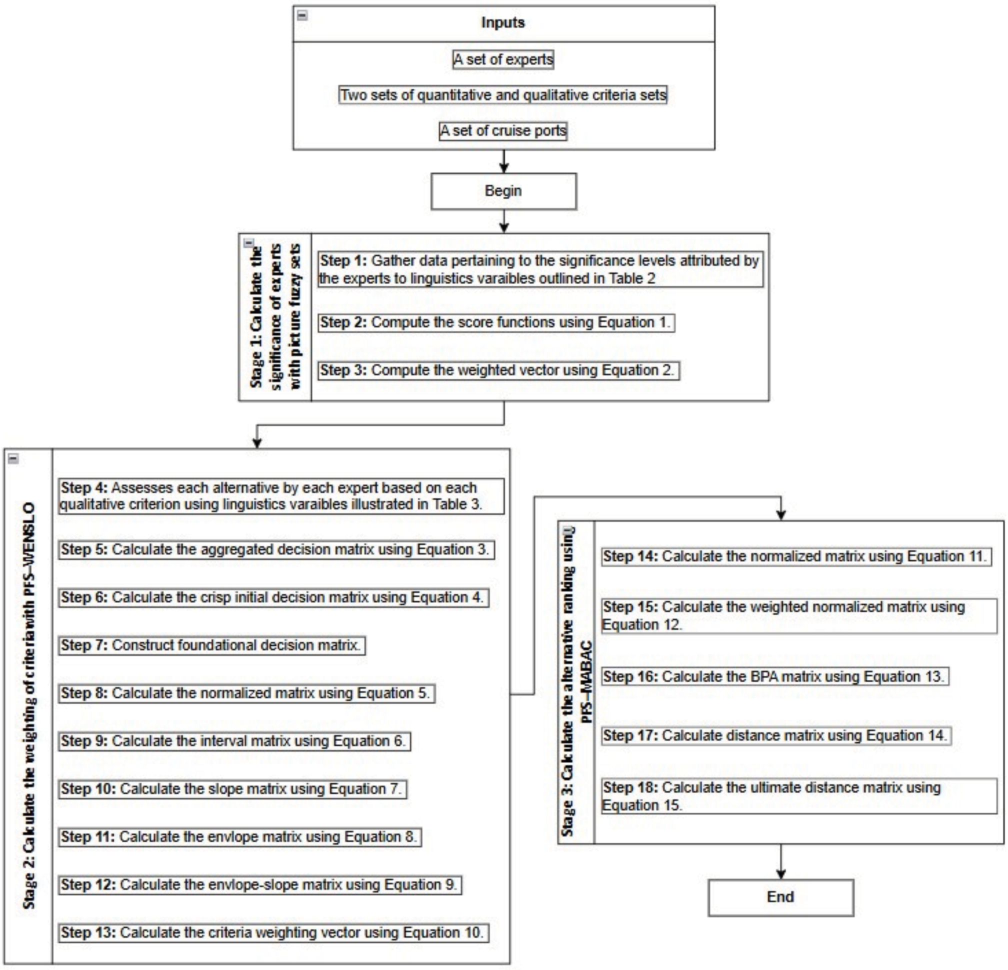

Figure 2. The diagram of PFS–WENSLO–MABAC
Abbreviations: BPA: Boundary proximity area; MABAC: Multi-attributive border approximation area comparison; PFS: Picture fuzzy set; WENSLO: Weights by envelope and slope.

Table 4. The expert group

Experts	**Significance levels**	**Professions**
Ω_1	Very important (VI)	Chief port officer
Ω_2	Important (I)	Operations/cruise terminal manager
Ω_3	Important (I)	Operations/cruise terminal manager
Ω_4	Very important (VI)	Operations director
Ω_5	Medium important (MI)	Terminal manager
Ω_6	Medium important (MI)	Terminal manager
Ω_7	Very important (VI)	Operations director
Ω_8	Medium important (MI)	Operations supervisor

ating cruise terminal performance, emphasizing the protection of passengers, vessels, and port operations. This criterion encompasses security measures, emergency preparedness, passenger safety protocols, and personnel training, highlighting its pivotal role in fostering a secure environment and influencing cruise destination selection.[55,56]

(iii) Port facilities and services ($\Psi_{3^{(ql)}}$): The evaluation of cruise port performance highlights the critical importance of port facilities and services, encompassing terminal amenities, accommodations, dining, shopping, access to attractions, guidance, and passenger transfers to ensure a high-quality experience for tourists and ships. This criterion further encompasses operational aspects, including ship–shore communication, pilotage, mooring, navigation, port state control, efficiency, and compliance with environmental regulations, reflecting its central role in overall port quality and tourist satisfaction.[57]

(iv) Connectivity ($\Psi_{4(ql)}$): The assessment of cruise port performance emphasizes the "connectivity" criterion, which evaluates a port's accessibility to various transportation modes, the city center, and nearby tourist attractions, thereby ensuring seamless integration with road, rail, air, and sea networks. This criterion also considers factors such as hinterland access, streamlined customs, immigration, and quarantine procedures, as well as proximity to airports, train stations, and highways, all of which influence the port's capacity to accommodate turnaround and transit cruise traffic.[58]

(v) Cruise port services costs ($\Psi_{5(ql)}$): The assessment of cruise port performance incorporates the "cruise port services costs" criterion, focusing on expenses related to port services such as docking, loading/unloading operations, security, and other essential support services for cruise ships. This criterion assesses the economic sustainability, operational efficiency, and financial risks associated with cruise operations, taking into account costs for port dues, passenger services, International Ship and Port Facility Security Code (ISPS) compliance, baggage handling, pilotage, towage, waste reception, bunkering, and shore office operations.[59,60]

(vi) Tourism attraction ($\Psi_{6(ql)}$): The evaluation of cruise port performance emphasizes the "tourism attraction" criterion, focusing on the appeal and accessibility of local tourist sites, cultural heritage, and historical landmarks near the port. This qualitative measure influences the duration of tourist stays and overall destination attractiveness, considering factors such as local language proficiency, cultural and natural resources, climate, and proximity to key attractions.[58]

(vii) Sustainability ($\Psi_{7(ql)}$): Sustainability is a critical criterion in evaluating cruise port performance, encompassing environmental, economic, and social dimensions, including waste management, resource utilization, community engagement, and labor conditions. The adoption of green terminal technologies, circular economy practices, and holistic management approaches addressing carbon footprint, energy efficiency, and social impacts underpins the long-term sustainability of ports and their surrounding cities.[61,62]

(viii) Number of cruise ships ($\Psi_{8(qn)}$): This criterion is a quantitative measure of cruise port performance, representing the total number of cruise ships that have docked at a port over the past year. It serves as a numerical indicator of the port's activity, popularity, and attractiveness within the cruise tourism sector, with data sourced from the Ministry of Transport and Infrastructure of Türkiye.[63]

(ix) Number of cruise passengers ($\Psi_{9(qn)}$): This criterion serves as a quantitative metric for evaluating cruise port performance. It signifies the total number of cruise passengers hosted by a port in the past year. A higher passenger count may reflect the port's popularity and attractiveness, indicating success in the cruise tourism sector. The data for this criterion were obtained from the Ministry of Transport and Infrastructure of Türkiye.[63]

Both the data for the "number of cruise ships" and the "number of cruise passengers" are presented in Appendix D.

4.1.3. Cruise port alternatives

In Türkiye, there are 19 cruise ports. The information pertaining to these cruise ports is as follows:

(i) Alanya cruise port (X_1): The Alanya cruise port, located along the Turkish Riviera, is strategically positioned 125 km from Antalya Airport and 42 km from Gazipaşa–Alanya Airport, featuring a medieval castle on a rocky peninsula and a favorable climate with 300 days of sunshine and an average sea temperature of 22°C. Designed exclusively for cruise ships and Kyrenia–Alanya fast ferries, the port provides access to the region's beaches, coves, canyons, rivers, caves, and culturally rich Mediterranean landscape, with the commercial center and bazaar within walking distance. The harbor area features bars, cafés, nightclubs, and venues hosting free cultural events, making Alanya a culturally significant and attractive cruise destination.[64]

(ii) Amasra cruise port (X_2): Administered by the Bartın Municipality, the port provides a comprehensive range of services, including pilotage, towage, fresh water supply, mooring, waste management, storage, and security. Operating internationally for both cargo and passenger traffic, it serves as a key customs gateway, accommodating vessels up to 215 m in length despite a nominal water depth of 7.5–8 m along its 480 m quay. Cruise passengers benefit from organized excursions to nearby destinations, such as Amasra and Safranbolu, which enhance the overall maritime tourism experience.

(iii) Antalya cruise port (X_3): Antalya is a versatile port facility featuring separate harbors for cruise ships, container vessels, bulk cargo ships, and a yacht marina. Its strategic location near an international airport, adjacent accommodations, and key archaeological sites establishes it as a leading homeport in the Mediterranean, contributing to Antalya's status as Türkiye's premier holiday destination with over 110 million annual visitors. Since the start of cruise operations in 2010, passenger numbers surged from 13,842 in 2009 to around 200,000 in 2015, supported by three cruise piers, a passenger terminal, luggage facilities, and comprehensive services including pilotage, tugging, mooring, security, and waste management.[65]

(iv) Bodrum cruise port (X_4): Bodrum cruise port, administered by Global Ports Holding, has established itself as a premier luxury destination for cruise lines, featuring a finger pier capable of accommodating two large vessels or four smaller ships simultaneously, with a 2011 extension allowing the berth of the world's largest cruise ships. The port also features three ferry ramps and quays for up to 30 mega yachts, offering comprehensive terminal, marine, and auxiliary services. Additionally, it boasts a modern terminal building with duty-free shops, travel agencies, and a restaurant. Strategically located within walking distance of the city center and 36 km from Milas–Bodrum Airport, the port ensures convenient accessibility, reinforcing its status as a highly desirable cruise destination.[66]

(v) Bozcaada cruise port (X_5): Bozcaada, Türkiye's third-largest island in the northeast Aegean Sea near the Dardanelles, spans 40 km^2, featuring 12 bays and 17 surrounding islets, and is renowned for its vineyards and wine production, which form a significant part of its cultural heritage. The island combines natural beauty, including crystal clear beaches, with a rich historical legacy, having been known as Leukophrys in antiquity and later as Tenedos, before adopting the name Bozcaada in the 16^{th} century. Located 12 nautical miles from the Dardanelles entrance and 3.4 nautical miles from the mainland, Bozcaada is accessible via a 25-minute ferry and is increasingly recognized as a favorable stop on Aegean and İstanbul cruise itineraries.[67]

(vi) Çanakkale cruise port (X_6): Established in 2005, the Port of Çanakkale is a multifaceted maritime facility handling bulk, general, liquid, chemical, container, roll-on/roll-off, and cruise operations, adhering to ISPS regulations and accommodating a wide range of vessels. Strategically located in the Strait of Çanakkale within the customs area, the port serves as a key conduit for tourism and trade, featuring a pier draft of 8.5–28 m, a total length of 214 m, and direct connectivity to the Bursa–Izmir highway via a 2 km private road.[68]

(vii) Çeşme cruise port (X_7): Situated on the Karaburun Peninsula west of İzmir, Çeşme is a prominent tourist destination in Türkiye's Aegean region, renowned for its turquoise waters, golden sand beaches, unspoiled bays, vibrant nightlife, historical sites such as Erythrai, and the nearby picturesque town of Alaçatı with its windmills and windsurfing beach. The strategically located Çeşme cruise port, within walking distance of the city center and marina, offers a pier near tourist amenities and facilitates ferry connections to the Greek island of Chios and the mainland port of Lavrion, reinforcing its role as a key maritime gateway.[69]

(viii) Dikili cruise port (X_8): Dikili, located in İzmir Province along the Aegean Sea, serves as both a port town and a cruise gateway to Pergamon, with a scenic shoreline and well-equipped maritime infrastructure. Dikili Port provides comprehensive services, including anchorage, cargo handling, pilotage, towing, mooring, water supply, waste management, passenger lounges, and security in compliance with ISPS standards, with recent upgrades enhancing operational efficiency and facilitating customs, health, and maritime police procedures.[70]

(ix) Fethiye cruise port (X_9): Fethiye, located on Türkiye's southwestern coast in Muğla Province, serves as a key maritime gateway along the Turkish Riviera, renowned for its scenic landscapes, crystal clear waters, and proximity to historical sites. The port offers comprehensive maritime services, including anchorage, cargo handling, pilotage, towing, mooring, water supply, waste collection, and passenger facilities, supporting both commercial and cruise operations. Its combination of natural beauty, ancient ruins such as Telmessos and Lycian rock-cut tombs, and modern amenities establishes Fethiye as an attractive and culturally rich destination for cruise travelers.

(x) Göcek cruise port (X_{10}): Göcek, located on Türkiye's southwestern coast within the Fethiye district, serves as a distinguished maritime center along the Turkish Riviera, celebrated for its azure waters, pristine bays, and lush landscapes. The port provides comprehensive maritime services, including anchorage, cargo handling, pilotage, towing, mooring, water supply, waste collection, and passenger facilities, supporting both cruise and commercial operations. Its proximity to historical sites such as Telmessos and Lycian rock-cut tombs, combined with modern amenities and traditional Turkish culture, makes Göcek cruise port an attractive destination for cruise travelers seeking a blend of natural beauty, cultural heritage, and maritime convenience.

(xi) Istanbul cruise port (X_{11}): Istanbul, straddling two continents, uniquely combines rich historical heritage with vibrant cultural experiences, featuring United Nations Educational, Scientific and Cultural Organization-recognized Byzantine and Ottoman architecture. At its core, Galataport Istanbul spans 1.2 km along the Bosphorus, hosting the world's first subterranean cruise terminal with a distinctive hatch system, while also serving as a mixed-use cultural, gastronomic, and leisure hub. Capable of accommodating three cruise ships simultaneously and implementing advanced COVID-19 precautions, Galataport Istanbul integrates landmarks such as the Istanbul Museum of Modern Art and Tophane Square, offering cruise passengers and visitors a distinctive and immersive urban maritime experience.[71]

(xii) İzmir cruise port (X_{12}): Located on Türkiye's western coast, İzmir combines a temperate climate with well-connected ports, airports, and highways, offering seamless accessibility for maritime and land travel. Port İzmir, situated in a sheltered bay, accommodates passenger ferries, cruise ships, and large container vessels, serving as a gateway to archaeological sites such as Ephesus, Sardis, and the Çeşme Peninsula. Celebrated as the "pearl of the Aegean," İzmir integrates 8500 years of history, picturesque coastlines, and vibrant cultural and commercial attractions, making it a compelling destination for both cruise tourists and cultural explorers.[72]

(xiii) Kaş cruise port (X_{13}): Kaş cruise port, located along Türkiye's Mediterranean coast, offers a well-equipped maritime facility providing anchorage, terminal services, pilotage, towing, mooring, water supply, and waste collection, while serving as a gateway to the region's picturesque landscapes and ancient ruins. The town's traditional architecture, vibrant local markets, and nearby pristine beaches enhance its appeal as a multifaceted destination for cruise travelers seeking both cultural exploration and maritime experiences.

(xiv) Kuşadası cruise port (X_{14}): Kuşadası Port, Türkiye's largest cruise port, serves as a key gateway to the Aegean region, providing access to historically significant sites such as Ephesus, Magnesia, and Priene, thereby attracting culturally oriented cruise tourists. Operated by Ege Port Joint Stock Company, the port offers comprehensive services including water and fuel supply, waste management, healthcare, tugging, pilotage, and customs facilitation, complemented by the Scala Nova mall with shops and restaurants to enhance the passenger experience.73

(xv) Marmaris cruise port (X_{15}): Marmaris, renowned for its scenic coastline, azure waters, pine-covered hills, and historical sites such as Marmaris Castle and Marina, has emerged as a prominent center for yacht tourism, Blue Voyages, and cruise liner visits. The Marmaris cruise port, strategically positioned near the town center and Gunnucek National Park, provides secure berths and comprehensive access to the region's natural beauty, cultural heritage, and recreational amenities.[74]

(xvi) Samsun cruise port (X_{16}): Samsun, celebrated for its historical significance as the starting point of Türkiye's modernization, combines cultural vibrancy with natural attractions such as Atakum Beach, the longest along the Black Sea coast. The Samsung Port, the largest in the region and uniquely equipped with a railway connection, serves as a strategic hub linking the city to an extensive hinterland and enhancing regional maritime and transportation networks.[75]

(xvii) Sinop cruise port (X_{17}): Sinop, located in northern Anatolia along the Black Sea, is a city distinguished by its rich historical heritage and scenic natural landscapes, featuring landmarks from the Roman, Seljuk, and Byzantine periods, including the well-preserved Sinop Fortress. Renowned as the birthplace of the third-century BC philosopher Diogenes the Cynic, the city offers cultural and recreational attractions such as Karakum Beach, Hamsilos Bay, Erfelek Waterfalls, and the historic Sinop Fortress Prison, now functioning as a museum.[72]

(xviii) Trabzon cruise port (X_{18}): Trabzon, located on the eastern coast of the Black Sea, serves as a strategic maritime hub connecting Türkiye with Bulgaria, Georgia, Moldova, and Russia, and plays a vital role in international trade and cruise tourism. Established in 1903 and modernized in 1990, Trabzon Port accommodates an average of 10 cruise ships annually and up to 2500 vessels for trade, underscoring its enduring significance in regional maritime connectivity.[72]

(xix) Ünye cruise port (X_{19}): Ünye, situated along Türkiye's Black Sea coast, has emerged as an important maritime hub with the development of Ünye cruise port, serving as a strategic gateway to the region's cultural and natural attractions. The port is equipped with essential facilities and services to ensure a seamless experience for cruise passengers, reinforcing Türkiye's commitment to enhancing its cruise tourism infrastructure and elevating the Black Sea's appeal as a destination.

The experts, criteria, and cruise ports are illustrated in **Figure 3**.

4.2. Evaluation of sustainable tourism performance of cruise ports

The introduced PFS–WENSLO–MABAC was employed to assess the performance of Turkish cruise ports in terms of tourism and sustainability. As illustrated in the algorithm, performance assessment should be conducted in three stages. The steps for each of the three stages are as follows, sequentially:

- **First stage**: Determining weights assigned to each expert.
  - **Step 1**: The influence levels within the decision process were considered as LVs to determine the impact levels of the eight experts on the decision-making process. Subsequently, these LVs were transformed into PFSs (**Table 2**). The key levels of expertise are presented in Table S1.
  - **Step 2**: The score functions $\mathcal{S}\left(\widetilde{\Omega}_{\mathfrak{r}}\right)$ $(\mathfrak{r} = \overline{1,\ 8})$ were computed using **Equation** (1). The values of the score functions are presented in Table S1.
  - **Step 3**: The experts' weighting matrix $\left(w = [w_{\mathfrak{r}}]_{\mathfrak{X}}\right)$ was calculated using **Equation** (2) (**Table 5**).

- **Second stage**: Calculating weights assigned to each criterion.
  - **Step 4**: The initial decision matrices $\left(\widetilde{\mathfrak{P}}^{(\widetilde{\Omega}_{\mathfrak{r}})} = \left[\widetilde{\mathfrak{P}}_{\mathfrak{z}\mathfrak{y}^{(ql)}}^{(\widetilde{\Omega}_{\mathfrak{r}})}\right]_{19x7}\right)$ for evaluating (with LVs) the cruise ports under the qualitative criteria were constructed after interviewing the experts. They are presented in Table S2. Then, LVs were transformed into PFS (Table S3).
  - **Step 5**: The aggregated decision matrix $\left(\widetilde{\mathfrak{P}} = \left[\widetilde{\mathfrak{P}}_{\mathfrak{z}\mathfrak{y}^{(ql)}}\right]_{19x7}\right)$ was calculated with picture fuzzy weighted average (**Equation** ((3))). It is presented in Table S4.
  - **Step 6**: The crisp initial decision matrix for the qualitative criteria $\left(\mathfrak{P} = \left[\mathfrak{P}_{\mathfrak{z}\mathfrak{y}^{(ql)}}\right]_{19x7}\right)$ was calculated using **Equation** (4) and is presented in Table S5.
  - **Step 7**: The foundational decision matrix $\left(\mathfrak{K} = [\mathfrak{K}_{\mathfrak{z}\mathfrak{y}}]_{19x9}\right)$ was obtained using the crisp initial decision matrices for both qualitative and quantitative criteria values. It is presented in Table S6.
  - **Step 8**: Using **Equation** (5), the normalization of the decision matrix $\left(\mathfrak{N} = [\mathfrak{N}_{\mathfrak{z}\mathfrak{y}}]_{19x9}\right)$ was calculated and presented in Table S7.
  - **Step 9**: The criterion class interval matrix $\left(\Delta\mathfrak{N}_{\mathfrak{y}} = [\Delta\mathfrak{N}_{\mathfrak{y}}]_{\mathfrak{Y}}\right)$ was calculated using **Equation** (6) and is presented in Table S8.
  - **Step 10**: The criterion class slope matrix $\left(tan\sigma_{\mathfrak{y}} = [tan\sigma_{\mathfrak{y}}]_{\mathfrak{Y}}\right)$ was calculated using **Equation** (7) and is presented in Table S8.

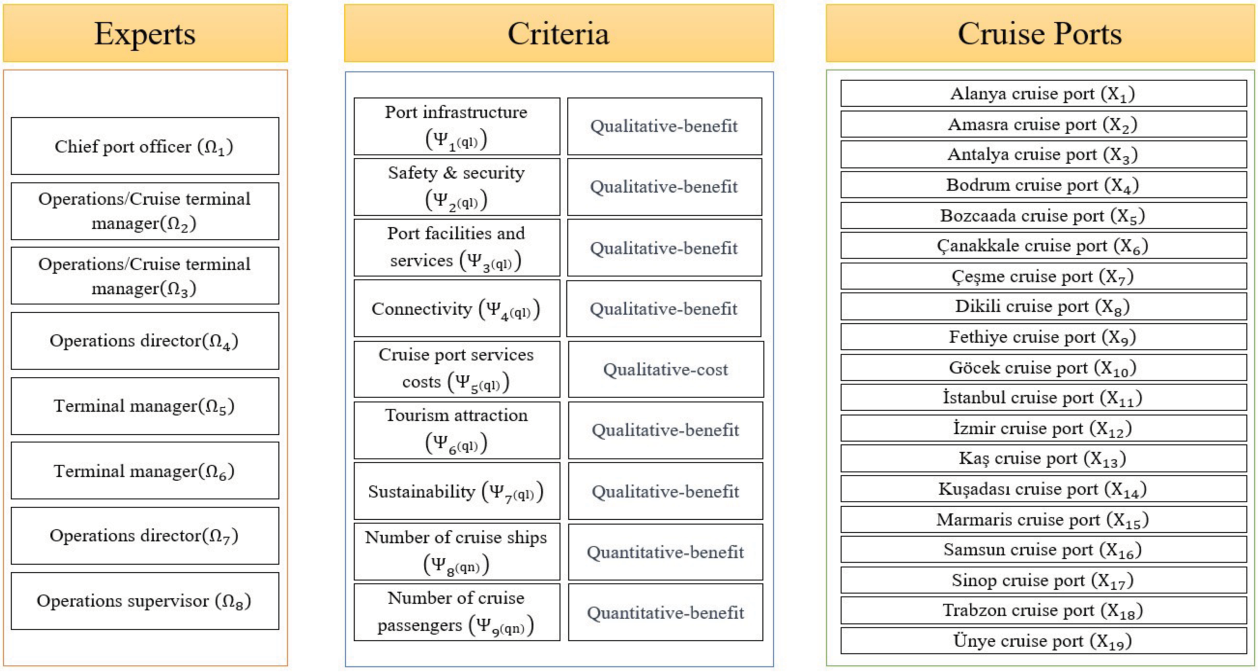

Figure 3. Case study decision model

Table 5. The experts' weighing matrix

Experts	Ω_1	Ω_2	Ω_3	Ω_4	Ω_5	Ω_6	Ω_7	Ω_8
$w_{\mathfrak{r}}$	0.1463	0.1381	0.1381	0.1463	0.0950	0.0950	0.1463	0.0950

Table 6. The criteria weigh matrix

Criteria	$\Psi_{1(ql)}$	$\Psi_{2(ql)}$	$\Psi_{3(ql)}$	$\Psi_{4(ql)}$	$\Psi_{5(ql)}$	$\Psi_{6(ql)}$	$\Psi_{7(ql)}$	$\Psi_{8(qn)}$	$\Psi_{9(qn)}$
$\mathbb{W}_{\mathfrak{y}}$	0.0040	0.0014	0.0035	0.0039	0.0017	0.0027	0.0008	0.4218	0.5601

- **Step 11**: The criterion envelope matrix $\left(E_{\mathfrak{y}} = [E_{\mathfrak{y}}]_{\mathfrak{Y}}\right)$ was calculated using **Equation** (8). It is presented in Table S8.
- **Step 12**: The criterion envelope–slope ratio matrix $\left(ES_{\mathfrak{y}} = [ES_{\mathfrak{y}}]_{\mathfrak{Y}}\right)$ was calculated using **Equation** (9) and presented in Table S8.
- **Step 13**: Using **Equation** (10), the criterion weighting matrix $\left(\mathbb{W}_{\mathfrak{y}} = [\mathbb{W}_{\mathfrak{y}}]_{\mathfrak{Y}}\right)$ was calculated (**Table 6**).

- **Third stage**: Determining rankings of the alternatives.
  - **Step 14**: Using **Equation** (11), the normalized decision matrix $\left(\mathfrak{I} = [\mathfrak{I}_{\mathfrak{z}\mathfrak{y}}]_{19x9}\right)$ was calculated. It is presented in Table S9.
  - **Step 15**: Using **Equation** (12), the weighted decision matrix $\left(\mathfrak{H} = [\mathfrak{H}_{\mathfrak{z}\mathfrak{y}}]_{19x9}\right)$ was calculated. It is presented in Table S10.
  - **Step 16:** Using **Equation** (13), the BPA matrix $\left(\mathfrak{F} = [\mathfrak{F}_{\mathfrak{z}}]_{\mathfrak{Z}}\right)$ was computed and presented in Table S11.
  - **Step 17**: Using **Equation** (14), the distance matrix of alternatives $\left(\mathfrak{E} = [\mathfrak{E}_{\mathfrak{z}\mathfrak{y}}]_{19x9}\right)$ was calculated and presented in Table S12.
  - **Step 18**: Using **Equation** (15), the ultimate distance matrix $\left(\mathfrak{D} = [\mathfrak{D}_{\mathfrak{z}}]_{\mathfrak{Z}}\right)$ of alternatives was computed (**Table 7**). The Kuşadası cruise port (X_{14}) showed the best performance (highest value).

5. Results and discussion

The primary motivation of this research is to develop a decision support system for assessing the performance of cruise ports in Türkiye in terms of their contributions to tourism and sustainability. Rather than relying solely on the evaluation

Table 7. Ultimate distance matrix

Alternatives	$\mathfrak{D}_{\mathfrak{z}}$
X_1	−0.0611
X_2	−0.069
X_3	−0.0415
X_4	0.0694
X_5	−0.073
X_6	−0.0444
X_7	0.0113
X_8	−0.0677
X_9	−0.0893
X_{10}	−0.0859
X_{11}	0.3818
X_{12}	−0.0434
X_{13}	−0.0868
X_{14}	0.9029
X_{15}	−0.0485
X_{16}	−0.0906
X_{17}	−0.0776
X_{18}	−0.0674
X_{19}	−0.0751

of tourist numbers, this decision support system incorporates a performance assessment of cruise ports based on qualitative criteria. The newly developed hybrid method and algorithm in this research evaluate the performance of cruise ports. To test the developed algorithm for this hybrid method, a case study was conducted in Türkiye, and the obtained results can be presented in three dimensions.

Firstly, a performance evaluation system based on expert opinions was developed. Secondly, a decision support system that allowed the combined use of qualitative and quantitative criteria was established. Thirdly, a different perspective on the performance evaluation approach of cruise ports in terms of their contribution to tourism was presented. This perspective considered the infrastructure, services, and sustainability criteria in creating a decision model.

In terms of prioritizing criteria, the results indicated that the importance levels of the number of tourists and the number of cruise ships approaching the ports were significantly higher compared to other qualitative criteria. Additionally, among the quantitative criteria, the most crucial criterion was the number of passengers. The prioritization of the importance levels of the criteria was as follows: number of cruise passengers $(\Psi_{9(qn)})$ > number of cruise ships $(\Psi_{8(qn)})$ > port infrastructure $(\Psi_{1(ql)})$ > connectivity $(\Psi_{4(ql)})$ > port facilities and services $(\Psi_{3(ql)})$ > tourism attraction $(\Psi_{6(ql)})$ > cruise port services costs $(\Psi_{5(ql)})$ > safety and security $(\Psi_{2(ql)})$ > sustainability" $(\Psi_{7(ql)})$. Surprisingly, sustainability is the least significant criterion in determining the performance of cruise ports in Türkiye, which contrasts with expectations. At this point, it can be concluded that expert judgments place greater emphasis on operational activities, port infrastructure, and tourism-related evaluations. On the other hand, it is expected that criteria indicating the number of passengers and cruise ships for tourism purposes would rank first and second, respectively.

In terms of the ranking of cruise ports for sustainable tourism, Kuşadası cruise port emerged as having the highest performance. The performance ranking of cruise ports for sustainable tourism was as follows: Kuşadası cruise port (X_{14}) > Istanbul cruise port (X_{11}) > Bodrum cruise port (X_4) > Çeşme cruise port (X_7) > Antalya cruise port (X_3) > İzmir cruise port (X_{12}) > Çanakkale cruise port (X_6) > Marmaris cruise port (X_{15}) > Alanya cruise port (X_1) > Trabzon cruise port (X_{18}) > Dikili cruise port (X_8) > Amasra cruise port (X_2) > Bozcaada cruise port (X_5) > Ünye cruise port (X_{19}) > Sinop cruise port (X_{17}) > Göcek cruise port (X_{10}) > Kaş cruise port (X_{13}) > Fethiye cruise port (X_9) > Samsun cruise port (X_{16}). The results suggest that the high weights of quantitative data in determining criteria priorities are reflected in the parallelism between sustainable tourism performances and the number of cruise ships and passengers approaching the ports. This conclusion supports the high importance levels of quantitative criteria.

Ultimately, the newly proposed PFS–WENSLO–MABAC hybrid model was successfully applied to assess the sustainable tourism performance of cruise ports in this study. PFSs provide a flexible and robust framework for decision-making for problems characterized by hesitant, conflicting, or incomplete information; however, they may introduce computational complexity and usability limitations for non-expert decision-makers. The WENSLO method enables more objective criterion weighting by relying on envelope–slope ratio-based calculations, while the MABAC method offers more sensitive and discriminative alternative ranking by evaluating distances to minimum and maximum boundary proximity areas. Consequently, the proposed PFS–WENSLO–MABAC hybrid model delivers a realistic and comprehensive decision-making framework that simultaneously incorporates both qualitative and quantitative criteria through robust and sophisticated computational procedures. Moreover, by jointly considering expert judgments and empirical performance data of cruise ports, the proposed approach provides a broader and more holistic perspective to support sustainable tourism decision-making.

Furthermore, the consistency exhibited by the obtained findings supports the effective utilization of the developed algorithm as a robust tool for measuring sustainable tourism performance. Compared to other conventional methods, PFS–WENSLO–MABAC demonstrates superior performance by integrating the flexibility of PFS to handle uncertainty and the robust weighting and ranking capabilities of WENSLO and MABAC, thereby providing a more comprehensive and reliable assessment of cruise port performance under complex and ambiguous decision-making conditions.

5.1. Sensitivity analysis

Sensitivity analysis scenarios (SAS) were established to assess the robustness levels of the proposed hybrid model and algorithm. SASs were created based on various scenarios, and the findings obtained from implementing these scenarios allowed for a comparison with the research results. In this study, SASs were established using two different approaches. In the first approach (SAS-1), the aim was to identify the changes in case criteria when a single criterion is excluded from the decision model. In the second approach (SAS-2), the goal was to identify changes in the findings when cruise ports are excluded. SAS-1 and SAS-2 scenarios were developed based on these two approaches, and sub-scenarios were created for each SAS. In SAS-1, each criterion in the decision model was individually excluded, resulting in nine sub-scenarios. In SAS-2, each cruise port was individually excluded, resulting in 19 sub-scenarios.

According to the sub-scenarios of SAS-1, each criterion was sequentially excluded from the decision model, and the algorithm was rerun. The prioritization of criteria is shown in **Table 8**. There is generally no change in the ranking of criterion importance levels. Only when the criterion number of cruise passengers ($\Psi_{9(q^n)}$) was excluded from the decision model, the number of cruise ships ($\Psi_{8(q^n)}$) was identified as the best criterion.

The cruise port performances obtained according to the sub-scenarios of SAS-1 are shown in **Figure 4**. No changes in cruise port performance were observed according to the SAS-1 subscenarios. Thus, it is supported that the hybrid model developed according to SAS-1 is robust.

In SAS-2, each cruise port was sequentially excluded from the decision model, and the hybrid model was reapplied. The prioritization of criterion importance levels for each sub-scenario is shown in **Table 9**. According to the sub-scenarios of SAS-2, only minor changes were observed. However, the criterion with the highest importance level remained the same, the number of cruise passengers ($\Psi_{9(q^n)}$).

According to the sub-scenarios of SAS-2, there were no significant changes in the rankings of the cruise ports (**Figure 5**). Only when the best-performing Kuşadası cruise port (X_{14}) was excluded from the decision model, Istanbul cruise port (X_{11}) was identified as the best-performing cruise port. Thus, it is supported that the recommended hybrid model is robust according to the SAS-2 scenarios.

5.2. Comparative analysis

To assess and demonstrate the robustness of the PFS–WENSLO–MABAC approach, the case study was conducted using various alternative ranking methods (alternative ranking order method accounting for two-step normalization, ARTASI, root assessment method, simple additive weighting). In this analysis, criterion weights were assumed to be equal, and the performance of cruise ports was determined accordingly. The final performance scores of the cruise ports are presented in **Figure 6**. Examining the correlation among the ranking results, the correlation coefficients were 0.9935 for MABAC–ARMOAN, 0.9760 for MABAC–ARTASI, and 0.9999 for both the MABAC–root assessment method and the MABAC–simple additive weighting method. **Figure 7** illustrates the rankings using a radar chart. Deviations were observed in the rankings generated by the alternative ranking order method, accounting for the two-step normalization method, while the rankings from the other methods were highly similar. Overall, the high correlation coefficients and consistency of the results support the robustness and reliability of the PFS–WENSLO–MABAC method.

5.3. Research implications

This research has several implications that contribute to both academic literature and practical applications within the domain of cruise tourism and port management. The key research implications are outlined below:

(i) Methodological advancements: The development of PFS–WENSLO–MABAC introduces a novel methodological approach for evaluating the performance of cruise ports.

Table 8. Prioritization of the criteria based on the sensitivity analysis scenario 1

SAS-1	**Criterion ranks**	**Excluded criteria**	Best criteria
SAS-1a	$\Psi_{9(qn)} > \Psi_{8(qn)} > \Psi_{4(ql)} > \Psi_{3(ql)} > \Psi_{6(ql)} > \Psi_{5(ql)} > \Psi_{2(ql)} > \Psi_{7(ql)}$	$\Psi_{1(ql)}$	$\Psi_{9(qn)}$
SAS-1b	$\Psi_{9(qn)} > \Psi_{8(qn)} > \Psi_{1(ql)} > \Psi_{4(ql)} > \Psi_{3(ql)} > \Psi_{6(ql)} > \Psi_{5(ql)} > \Psi_{7(ql)}$	$\Psi_{2(ql)}$	$\Psi_{9(qn)}$
SAS-1c	$\Psi_{9(qn)} > \Psi_{8(qn)} > \Psi_{1(ql)} > \Psi_{4(ql)} > \Psi_{6(ql)} > \Psi_{5(ql)} > \Psi_{2(ql)} > \Psi_{7(ql)}$	$\Psi_{3(ql)}$	$\Psi_{9(qn)}$
SAS-1d	$\Psi_{9(qn)} > \Psi_{8(qn)} > \Psi_{1(ql)} > \Psi_{3(ql)} > \Psi_{6(ql)} > \Psi_{5(ql)} > \Psi_{2(ql)} > \Psi_{7(ql)}$	$\Psi_{4(ql)}$	$\Psi_{9(qn)}$
SAS-1e	$\Psi_{9(qn)} > \Psi_{8(qn)} > \Psi_{1(ql)} > \Psi_{4(ql)} > \Psi_{3(ql)} > \Psi_{6(ql)} > \Psi_{2(ql)} > \Psi_{7(ql)}$	$\Psi_{5(ql)}$	$\Psi_{9(qn)}$
SAS-1f	$\Psi_{9(qn)} > \Psi_{8(qn)} > \Psi_{1(ql)} > \Psi_{4(ql)} > \Psi_{3(ql)} > \Psi_{5(ql)} > \Psi_{2(ql)} > \Psi_{7(ql)}$	$\Psi_{6(ql)}$	$\Psi_{9(qn)}$
SAS-1g	$\Psi_{9(qn)} > \Psi_{8(qn)} > \Psi_{1(ql)} > \Psi_{4(ql)} > \Psi_{3(ql)} > \Psi_{6(ql)} > \Psi_{5(ql)} > \Psi_{2(ql)}$	$\Psi_{7(ql)}$	$\Psi_{9(qn)}$
SAS-1h	$\Psi_{9(qn)} > \Psi_{1(qn)} > \Psi_{4(ql)} > \Psi_{3(ql)} > \Psi_{6(ql)} > \Psi_{5(ql)} > \Psi_{2(ql)} > \Psi_{7(ql)}$	$\Psi_{8(qn)}$	$\Psi_{9(qn)}$
SAS-1i	$\Psi_{8(qn)} > \Psi_{1(qn)} > \Psi_{4(ql)} > \Psi_{3(ql)} > \Psi_{6(ql)} > \Psi_{5(ql)} > \Psi_{2(ql)} > \Psi_{7(ql)}$	$\Psi_{9(qn)}$	$\Psi_{8(qn)}$

Abbreviation: SAS, Sensitivity analysis scenario.

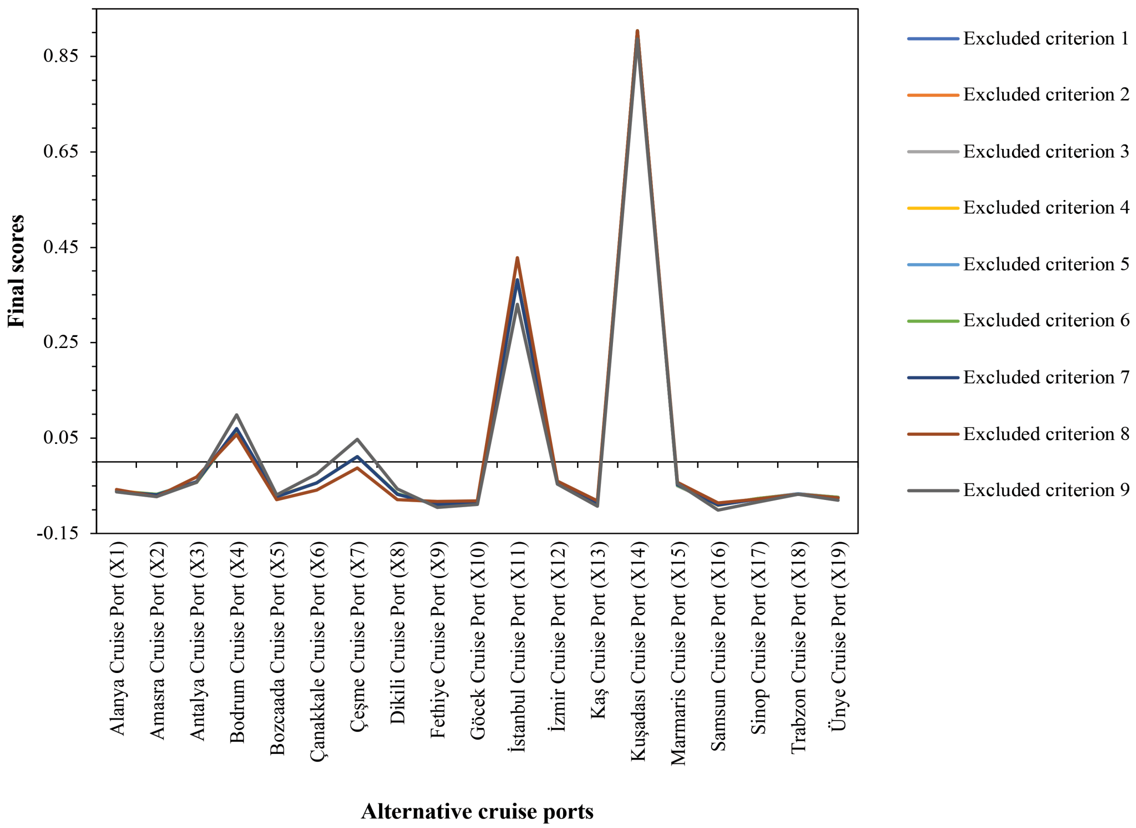

Figure 4. The prioritization of the alternatives (SAS-1).
Abbreviation: SAS: Sensitivity analysis scenario

This methodology combines the strengths of PFSs, WENSLO, and MABAC, showcasing the potential for integrating diverse methodologies into complex decision-making scenarios.

(ii) Integrated tool for performance assessment: The designed tool offers a comprehensive approach by integrating both qualitative and quantitative criteria in the performance evaluation of cruise ports. This integrated tool

Table 9. Prioritization of the criteria based on the sensitivity analysis scenario 2

SAS-2	Criterion ranks	Excluded alternative	Best criteria
SAS-2a	$\Psi_{9(qn)} > \Psi_{8(qn)} > \Psi_{1(ql)} > \Psi_{4(ql)} > \Psi_{3(ql)} > \Psi_{6(ql)} > \Psi_{5(ql)} > \Psi_{2(ql)} > \Psi_{7(ql)}$	X_1	$\Psi_{9(qn)}$
SAS-2b	$\Psi_{9(qn)} > \Psi_{8(qn)} > \Psi_{1(ql)} > \Psi_{4(ql)} > \Psi_{3(ql)} > \Psi_{6(ql)} > \Psi_{5(ql)} > \Psi_{2(ql)} > \Psi_{7(ql)}$	X_2	$\Psi_{9(qn)}$
SAS-2c	$\Psi_{9(qn)} > \Psi_{8(qn)} > \Psi_{1(ql)} > \Psi_{4(ql)} > \Psi_{3(ql)} > \Psi_{6(ql)} > \Psi_{5(ql)} > \Psi_{2(ql)} > \Psi_{7(ql)}$	X_3	$\Psi_{9(qn)}$
SAS-2d	$\Psi_{9(qn)} > \Psi_{8(qn)} > \Psi_{4(ql)} > \Psi_{1(ql)} > \Psi_{3(ql)} > \Psi_{6(ql)} > \Psi_{5(ql)} > \Psi_{2(ql)} > \Psi_{7(ql)}$	X_4	$\Psi_{9(qn)}$
SAS-2e	$\Psi_{9(qn)} > \Psi_{8(qn)} > \Psi_{1(ql)} > \Psi_{3(ql)} > \Psi_{4(ql)} > \Psi_{6(ql)} > \Psi_{5(ql)} > \Psi_{2(ql)} > \Psi_{7(ql)}$	X_5	$\Psi_{9(qn)}$
SAS-2f	$\Psi_{9(qn)} > \Psi_{8(qn)} > \Psi_{1(ql)} > \Psi_{4(ql)} > \Psi_{3(ql)} > \Psi_{6(ql)} > \Psi_{5(ql)} > \Psi_{2(ql)} > \Psi_{7(ql)}$	X_6	$\Psi_{9(qn)}$
SAS-2g	$\Psi_{9(qn)} > \Psi_{8(qn)} > \Psi_{1(ql)} > \Psi_{4(ql)} > \Psi_{3(ql)} > \Psi_{6(ql)} > \Psi_{5(ql)} > \Psi_{2(ql)} > \Psi_{7(ql)}$	X_7	$\Psi_{9(qn)}$
SAS-2h	$\Psi_{9(qn)} > \Psi_{8(qn)} > \Psi_{1(ql)} > \Psi_{4(ql)} > \Psi_{3(ql)} > \Psi_{6(ql)} > \Psi_{5(ql)} > \Psi_{2(ql)} > \Psi_{7(ql)}$	X_8	$\Psi_{9(qn)}$
SAS-2i	$\Psi_{9(qn)} > \Psi_{8(qn)} > \Psi_{1(ql)} > \Psi_{4(ql)} > \Psi_{3(ql)} > \Psi_{6(ql)} > \Psi_{5(ql)} > \Psi_{2(ql)} > \Psi_{7(ql)}$	X_9	$\Psi_{9(qn)}$
SAS-2j	$\Psi_{9(qn)} > \Psi_{8(qn)} > \Psi_{4(ql)} > \Psi_{1(ql)} > \Psi_{3(ql)} > \Psi_{6(ql)} > \Psi_{5(ql)} > \Psi_{2(ql)} > \Psi_{7(ql)}$	X_{10}	$\Psi_{9(qn)}$
SAS-2k	$\Psi_{9(qn)} > \Psi_{8(qn)} > \Psi_{4(ql)} > \Psi_{1(ql)} > \Psi_{3(ql)} > \Psi_{6(ql)} > \Psi_{5(ql)} > \Psi_{2(ql)} > \Psi_{7(ql)}$	X_{11}	$\Psi_{9(qn)}$
SAS-2l	$\Psi_{9(qn)} > \Psi_{8(qn)} > \Psi_{4(ql)} > \Psi_{1(ql)} > \Psi_{3(ql)} > \Psi_{6(ql)} > \Psi_{5(ql)} > \Psi_{2(ql)} > \Psi_{7(ql)}$	X_{12}	$\Psi_{9(qn)}$
SAS-2m	$\Psi_{9(qn)} > \Psi_{8(qn)} > \Psi_{1(ql)} > \Psi_{3(ql)} > \Psi_{4(ql)} > \Psi_{6(ql)} > \Psi_{5(ql)} > \Psi_{2(ql)} > \Psi_{7(ql)}$	X_{13}	$\Psi_{9(qn)}$
SAS-2n	$\Psi_{9(qn)} > \Psi_{8(qn)} > \Psi_{1(ql)} > \Psi_{3(ql)} > \Psi_{4(ql)} > \Psi_{6(ql)} > \Psi_{5(ql)} > \Psi_{2(ql)} > \Psi_{7(ql)}$	X_{14}	$\Psi_{9(qn)}$
SAS-2o	$\Psi_{9(qn)} > \Psi_{8(qn)} > \Psi_{1(ql)} > \Psi_{4(ql)} > \Psi_{3(ql)} > \Psi_{6(ql)} > \Psi_{5(ql)} > \Psi_{2(ql)} > \Psi_{7(ql)}$	X_{15}	$\Psi_{9(qn)}$
SAS-2p	$\Psi_{9(qn)} > \Psi_{8(qn)} > \Psi_{4(ql)} > \Psi_{1(ql)} > \Psi_{3(ql)} > \Psi_{6(ql)} > \Psi_{5(ql)} > \Psi_{2(ql)} > \Psi_{7(ql)}$	X_{16}	$\Psi_{9(qn)}$
SAS-2r	$\Psi_{9(qn)} > \Psi_{8(qn)} > \Psi_{1(ql)} > \Psi_{4(ql)} > \Psi_{3(ql)} > \Psi_{6(ql)} > \Psi_{5(ql)} > \Psi_{2(ql)} > \Psi_{7(ql)}$	X_{17}	$\Psi_{9(qn)}$
SAS-2s	$\Psi_{9(qn)} > \Psi_{8(qn)} > \Psi_{4(ql)} > \Psi_{1(ql)} > \Psi_{3(ql)} > \Psi_{6(ql)} > \Psi_{5(ql)} > \Psi_{2(ql)} > \Psi_{7(ql)}$	X_{18}	$\Psi_{9(qn)}$
SAS-2t	$\Psi_{9(qn)} > \Psi_{8(qn)} > \Psi_{4(ql)} > \Psi_{1(ql)} > \Psi_{3(ql)} > \Psi_{6(ql)} > \Psi_{5(ql)} > \Psi_{2(ql)} > \Psi_{7(ql)}$	X_{19}	$\Psi_{9(qn)}$

Abbreviation: SAS, sensitivity analysis scenario.

can serve as a benchmark for future studies and industry applications seeking a holistic understanding of performance.

(iii) Case study validation: The case study conducted in Türkiye validates the practical applicability and effectiveness of the developed hybrid model in a real-world scenario. This not only contributes to the understanding of cruise terminal performance in Türkiye but also serves as a reference for similar studies in different geographical locations.

(iv) Sensitivity analyses for robustness: The incorporation of sensitivity analyses, exploring various scenarios, adds a layer of robustness to the proposed hybrid model. Researchers and practitioners can adapt these sensitivity analyses to different contexts, enhancing the model's versatility.

(v) Contribution to cruise tourism development: The study contributes to the enhancement of cruise tourism by providing a tool for assessing and improving the performance of cruise ports. This, in turn, supports the overall development and competitiveness of cruise tourism destinations.

(vi) Benchmarking and comparison: The study facilitates benchmarking and comparison of cruise terminal performance, not only within

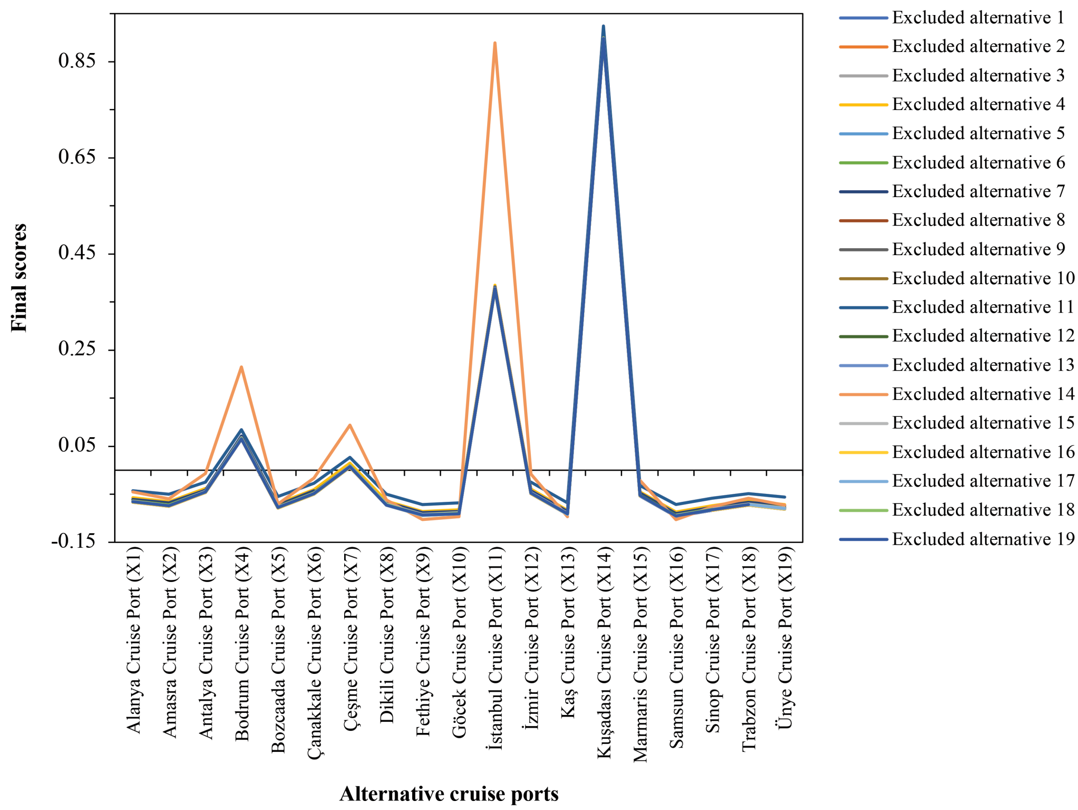

Figure 5. Prioritization of the alternatives (SAS-2)
Abbreviation: SAS, sensitivity analysis scenario.

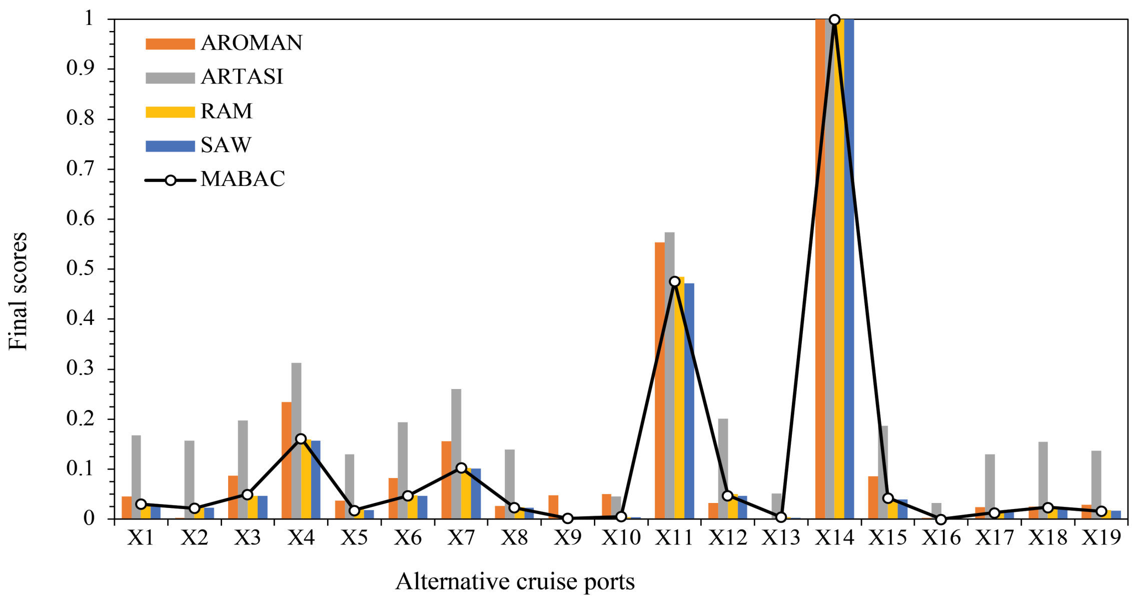

Figure 6. Comparative analysis results
Abbreviations: AROMAN: Alternative ranking order method accounting for two-step normalization; ARTASI: Alternative ranking technique based on adaptive standardized intervals; RAM: Root assessment method; SAW: Simple additive weighting; MABAC: Multi-attributive border approximation area comparison.

Türkiye but also on an international scale. This can drive healthy competition, encourage best practices, and contribute to the global advancement of cruise tourism infrastructure.

(vii) Holistic measurement of performance: The integration of both qualitative and quantitative criteria ensures a holistic measurement of cruise terminal performance. This contributes to a more accurate representation

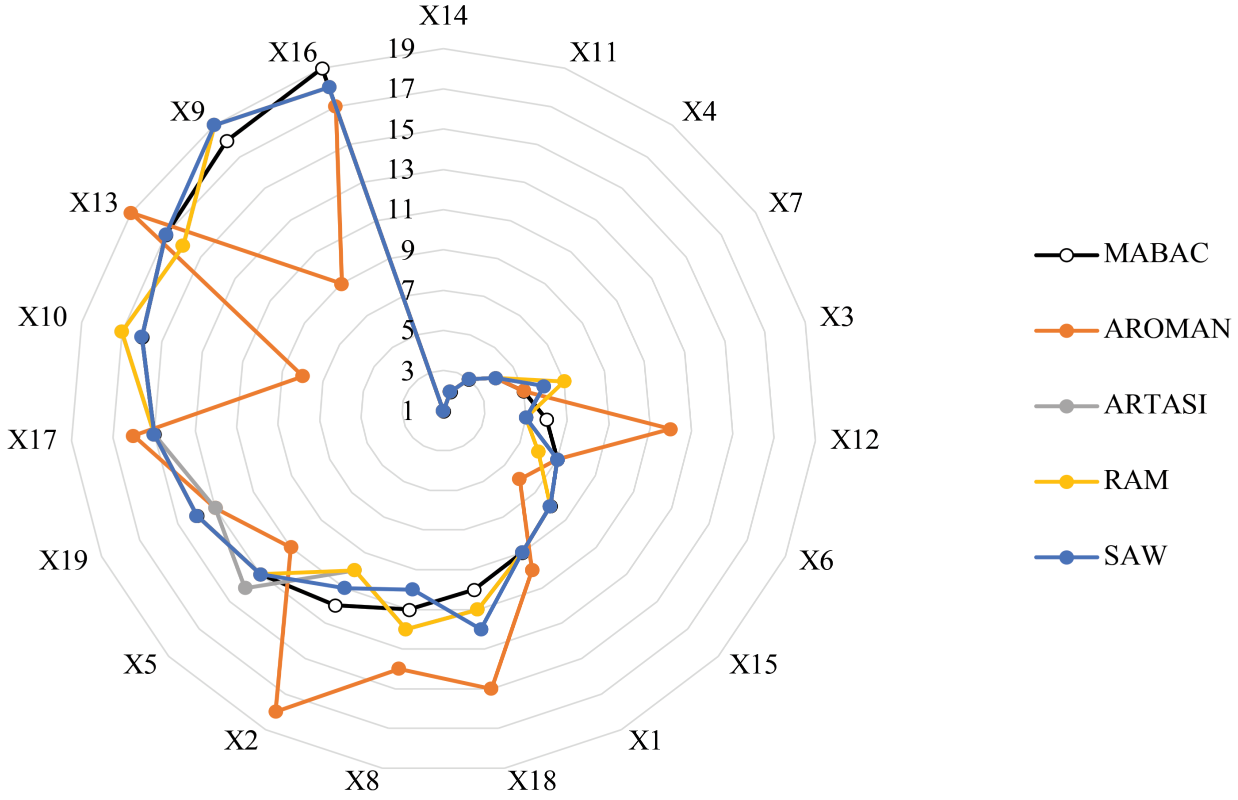

Figure 7. Performance ranking according to comparative results
Abbreviations: AROMAN: Alternative ranking order method accounting for two-step normalization; ARTASI: Alternative ranking technique based on adaptive standardized intervals; RAM: Root assessment method; SAW: Simple additive weighting; MABAC: Multi-attributive border approximation area comparison.

of the multifaceted nature of cruise tourism and the associated port services.

In summary, the research implications extend beyond the specific context of cruise terminal performance evaluation, offering methodological advancements, practical tools, and valuable insights with broader applications for decision-making in the field of maritime tourism and port management.

5.4. Managerial implications

The findings of this research offer valuable insights and practical implications for cruise terminal managers, executives, and decision-makers within the cruise tourism industry. The following managerial implications are highlighted below:

(i) Targeted performance improvement planning: Port authorities can use the criterion-level performance scores generated by the model to develop annual improvement roadmaps. Specifically, criteria with lower boundary proximity values should be prioritized in operational planning, enabling managers to design targeted corrective actions rather than broad, non-specific improvement initiatives.

(ii) Evidence-based resource allocation: The WENSLO-derived criterion weights allow decision-makers to allocate financial and human resources proportionally to their impact on overall port performance. For example, higher-weighted operational or infrastructure-related criteria should receive priority funding in port investment and modernization programs.

(iii) Strategic infrastructure and service upgrades: Based on MABAC rankings, port executives can identify whether performance deficiencies stem from physical infrastructure, service quality, or operational efficiency, and accordingly decide whether investments should focus on terminal expansion, passenger handling systems, digitalization, or service process redesign.

(iv) Institutionalization of expert-based evaluations: The integration of PFS-based expert assessments demonstrates the importance of systematically incorporating stakeholder knowledge into decision-making. Port authorities are encouraged to establish expert advisory panels (e.g., port managers, cruise operators, tourism officials) and periodically update evaluations to reflect evolving operational conditions.

(v) Scenario-based strategic resilience: The sensitivity and scenario analyses enable port managers to test the robustness of strategic decisions under varying assumptions, such as changes in criterion importance or demand conditions. This supports proactive risk management and enhances resilience against market volatility.

(vi) Benchmarking and inter-port comparison: The performance rankings allow port authorities to benchmark their terminals against competing cruise ports at national or regional levels. Such comparisons can inform competitive positioning strategies and support policy formulation aimed at strengthening cruise tourism hubs.

(vii) Data-driven stakeholder communication: The transparent and structured evaluation results can be used by port authorities to communicate performance outcomes to investors, regulators, and tourism stakeholders, thereby improving accountability and supporting evidence-based negotiations for funding and partnerships.

(viii) Continuous performance monitoring: Port authorities are advised to adopt the proposed hybrid model as a periodic performance monitoring tool, enabling continuous assessment and timely strategic adjustments in response to operational or environmental changes.

6. Conclusion

The primary objective of this study was to develop a comprehensive and robust decision-support framework for evaluating the sustainable tourism performance of cruise ports, incorporating both qualitative and quantitative criteria simultaneously. To achieve this objective, a novel hybrid model integrating PFS, the WENSLO weighting method, and the MABAC ranking technique was proposed and applied to Turkish cruise ports.

The empirical findings demonstrated that the proposed PFS–WENSLO–MABAC framework is capable of effectively capturing the complex and multidimensional nature of cruise port performance. The numerical results revealed clear differentiation among cruise terminals, enabling a transparent and interpretable ranking based on operational efficiency, service quality, infrastructure adequacy, and tourism-related performance indicators. The WENSLO-based weighting results indicated that operational and service-oriented criteria exerted a stronger influence on overall performance rankings, while sustainability-related criteria received comparatively lower weights under expert-driven evaluations. Although this outcome was unexpected, it reflects the current practical priorities of industry experts and highlights an important gap between the discourse on sustainability and operational decision-making in cruise port management.

The MABAC-based ranking results further demonstrated the stability and discriminatory power of the proposed framework. Sensitivity and scenario-based analyses confirmed that the relative rankings of cruise ports remained largely consistent under variations in criteria weights, indicating the robustness and reliability of the model. These numerical findings validated the applicability of the proposed framework in real-world decision-making environments characterized by uncertainty, vagueness, and expert subjectivity.

From a theoretical perspective, this study contributes to the literature by introducing a novel integration of PFS with WENSLO and MABAC, offering a mathematically coherent and flexible structure for handling incomplete, hesitant, and conflicting information. Methodologically, the study advances cruise port performance evaluation by providing a unified framework that bridges fuzzy decision modeling with objective weighting and distance-based ranking techniques.

From a practical standpoint, the findings offer actionable insights for port authorities, terminal operators, and policymakers by identifying critical performance gaps and prioritizing areas for improvement. The benchmarking of Turkish cruise ports also establishes a foundation for future comparative and cross-country studies, providing evidence-based support for strategic planning in the development of cruise tourism.

Despite the contributions of this research, several limitations must be acknowledged. The study focused primarily on cruise ports in Türkiye, which may limit the generalizability of the findings to other regions with differing infrastructure, tourism policies, and industry practices. The model's accuracy and reliability depend on the quality and completeness of the available data, and incomplete or imprecise information can introduce bias. Furthermore, the reliance on expert judgments introduces a degree of subjectivity, despite the mitigating effects of the PFS framework. Although the PFS framework was employed to effectively manage uncertainty and hesitation, the decision-making process still relies on expert judgments to a certain extent. To address potential concerns regarding subjectivity, the selection of eight experts was based on their demonstrated domain expertise, professional experience, and familiarity with cruise port operations, which is consistent with sample sizes commonly adopted in expert-based MCDM studies. Moreover, the use of group decision-making and aggregation mechanisms within the proposed framework helps to mitigate individual bias and enhances the reliability of the evaluation results. The dynamic nature of the cruise tourism industry, influenced by global events, economic fluctuations, and geopolitical shifts, may also impact the model's long-term applicability. Since the empirical analysis relies exclusively on data from 2024, the effects of time-period variability and seasonality are not considered, representing a limitation of the study. Lastly, the perspectives of broader stakeholders, including cruise operators, local communities, and passengers, were not incorporated, potentially omitting additional influential factors in cruise terminal performance.

Building upon the current research, several avenues for future studies are proposed. A cross-national comparative analysis of cruise port performance and the other types of ports could illuminate the effects of cultural, economic, and regulatory variations, fostering a global perspective on terminal dynamics. Longitudinal studies can track performance trends over time, identifying key milestones, potential improvements, and long-term industry patterns. However, it is worth noting that PFS–WENSLO–MABAC may require increased computational time and memory for processing larger datasets due to the complexity of fuzzy calculations and multi-criteria aggregation. Scenario planning and resilience modeling would enable the assessment of cruise ports' adaptability to crises, such as pandemics or geopolitical disruptions. Integrating passenger experience metrics would provide a more comprehensive evaluation by incorporating service quality, satisfaction, and the overall travel experience. Finally, assessing the impact of evolving national and international policies and regulations would enhance understanding of strategic and operational influences on cruise terminal performance.

By pursuing these future research directions, scholars and practitioners can advance a comprehensive understanding of cruise port operations, address emerging challenges, and promote sustainable growth in the global cruise tourism sector.

Abbreviations

Abbreviations	Full forms
ARTASI	Alternative ranking technique based on adaptive standardized intervals
MABAC	Multi-attributive border approximation area comparison
MCDM	Multi-criteria decision-making
PFSs	Picture fuzzy sets
SAS	Sensitivity analysis scenario
TOPSIS	Technique for order preference by similarity to the ideal solution
WENSLO	Weights by envelope and slope

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The authors declare they have no competing interests.

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Writing–review & editing: All authors

Availability of data

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AI tools statement

All authors confirm that no AI tools were used in the preparation of this manuscript.

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APPENDIX

Appendix A: Preliminaries of picture fuzzy sets

Definition 1. In the defined domain of discussion, denoted as $\mathfrak{S}$, the notation $\widetilde{\mathfrak{R}}$, as expressed in **Equation (**(A1)), indicates the presence of PFSs operating within the comprehensive context of the set $\mathfrak{S}$, as described by Ref. 41:

$$\widetilde{\mathfrak{R}} = \left\{ \left\langle \mathfrak{s},\ \theta_{\widetilde{\mathfrak{R}}}(\mathfrak{s}), \eta_{\widetilde{\mathfrak{R}}}(\mathfrak{s}), \zeta_{\widetilde{\mathfrak{R}}}(\mathfrak{s})\ \mid, \mathfrak{s} \in \mathfrak{S} \right\rangle \right\} \tag{A1}$$

In the examined framework, the functions $\theta_{\widetilde{\mathfrak{R}}}(\mathfrak{s}) : \widetilde{\mathfrak{R}} \to [0,1]$, $\eta_{\widetilde{\mathfrak{R}}}(\mathfrak{s}) : \widetilde{\mathfrak{R}} \to [0,1]$, and $\zeta_{\widetilde{\mathfrak{R}}}(\mathfrak{s}) : \widetilde{\mathfrak{R}} \to [0,1]$ can be interpreted as representing positive, neutral, and negative membership, respectively. These functions are systematically defined, adhering to the essential condition $0 \leq \theta_{\widetilde{\mathfrak{R}}}(\mathfrak{s}) + \eta_{\widetilde{\mathfrak{R}}}(\mathfrak{s}) + \zeta_{\widetilde{\mathfrak{R}}}(\mathfrak{s}) \leq 1$, valid for all elements $\mathfrak{s}$ within set $\mathfrak{S}$. Additionally, $\delta_{\widetilde{\mathfrak{R}}}(\mathfrak{s})$ is the degree of refusal-membership for the function, calculated as $\delta_{\widetilde{\mathfrak{R}}}(\mathfrak{s}) = 1 - \left(\theta_{\widetilde{\mathfrak{R}}}(\mathfrak{s}) + \eta_{\widetilde{\mathfrak{R}}}(\mathfrak{s}) + \zeta_{\widetilde{\mathfrak{R}}}(\mathfrak{s})\right)$. Furthermore, if $\delta_{\widetilde{\mathfrak{R}}}(\mathfrak{s}) = 0$ for all elements $\mathfrak{s}$ in the set $\mathfrak{S}$, the PFSs transition into intuitionistic fuzzy sets. Similarly, when $\delta_{\widetilde{\mathfrak{R}}}(\mathfrak{s}) = \eta_{\widetilde{\mathfrak{R}}}(\mathfrak{s}) = 0$ for all elements $\mathfrak{s}$ in the set $\mathfrak{S}$, the PFSs transform into fuzzy sets.[41]

Definition 2. Consider the presence of three entities representing PFSs, denoted as $\widetilde{\mathfrak{R}}$, $\widetilde{\mathfrak{R}}_1$, and $\widetilde{\mathfrak{R}}_2$, established within the universal set $\mathfrak{S}$. Their respective components are articulated as follows: $\widetilde{\mathfrak{R}} = \left(\theta_{\widetilde{\mathfrak{R}}}(\mathfrak{s}), \eta_{\widetilde{\mathfrak{R}}}(\mathfrak{s}), \zeta_{\widetilde{\mathfrak{R}}}(\mathfrak{s})\right)$, $\widetilde{\mathfrak{R}}_1 = \left(\theta_{\widetilde{\mathfrak{R}}_1}(\mathfrak{s}), \eta_{\widetilde{\mathfrak{R}}_1}(\mathfrak{s}), \zeta_{\widetilde{\mathfrak{R}}_1}(\mathfrak{s})\right)$, and $\widetilde{\mathfrak{R}}_2 = \left(\theta_{\widetilde{\mathfrak{R}}_2}(\mathfrak{s}), \eta_{\widetilde{\mathfrak{R}}_2}(\mathfrak{s}), \zeta_{\widetilde{\mathfrak{R}}_2}(\mathfrak{s})\right)$. The guiding principles governing the interrelationships among these three entities of PFSs are elaborated as follows (**Equations (**(A2)**)–(**(A5))):

$$\begin{aligned}\widetilde{\mathfrak{R}}_1 \oplus \widetilde{\mathfrak{R}}_2 = \Big\{ & \left(\left(\left(\theta_{\widetilde{\mathfrak{R}}_1}(\mathfrak{s})\right) + \left(\theta_{\widetilde{\mathfrak{R}}_2}(\mathfrak{s})\right) - \left(\theta_{\widetilde{\mathfrak{R}}_1}(\mathfrak{s})\,\theta_{\widetilde{\mathfrak{R}}_2}(\mathfrak{s})\right)\right),\right.\\ & \left.\left(\left(\eta_{\widetilde{\mathfrak{R}}_1}(\mathfrak{s})\right)\left(\eta_{\widetilde{\mathfrak{R}}_2}(\mathfrak{s})\right)\right), \left(\left(\zeta_{\widetilde{\mathfrak{R}}_1}(\mathfrak{s})\right)\left(\zeta_{\widetilde{\mathfrak{R}}_2}(\mathfrak{s})\right)\right)\right) \mid \mathfrak{s} \in \mathfrak{S}\Big\}\end{aligned} \tag{A2}$$

$$\begin{aligned}\widetilde{\mathfrak{R}}_1 \int \widetilde{\mathfrak{R}}_2 = \Big\{ & \left(\left(\left(\theta_{\widetilde{\mathfrak{R}}_1}(\mathfrak{s})\right)\left(\theta_{\widetilde{\mathfrak{R}}_2}(\mathfrak{s})\right)\right), \left(\left(\eta_{\widetilde{\mathfrak{R}}_1}(\mathfrak{s})\right) + \left(\eta_{\widetilde{\mathfrak{R}}_2}(\mathfrak{s})\right) - \left(\eta_{\widetilde{\mathfrak{R}}_1}(\mathfrak{s})\,\eta_{\widetilde{\mathfrak{R}}_2}(\mathfrak{s})\right)\right),\right.\\ & \left.\left(\left(\zeta_{\widetilde{\mathfrak{R}}_1}(\mathfrak{s})\right) + \left(\zeta_{\widetilde{\mathfrak{R}}_2}(\mathfrak{s})\right) - \left(\zeta_{\widetilde{\mathfrak{R}}_1}(\mathfrak{s})\,\zeta_{\widetilde{\mathfrak{R}}_2}(\mathfrak{s})\right)\right)\right) \mid \mathfrak{s} \in \mathfrak{S}\Big\}\end{aligned} \tag{A3}$$

$$\varpi\widetilde{\mathfrak{R}} = \left\{ \left(\left(1 - \left(1 - \left(\theta_{\widetilde{\mathfrak{R}}}(\mathfrak{s})\right)\right)^{\varpi}\right), \left(\eta_{\widetilde{\mathfrak{R}}}(\mathfrak{s})\right)^{\varpi}, \left(\zeta_{\widetilde{\mathfrak{R}}}(\mathfrak{s})\right)^{\varpi}\right) \mid \mathfrak{s} \in \mathfrak{S}\right\} \text{ for } \varpi > 0 \tag{A4}$$

$$\widetilde{\mathfrak{R}}^{\varpi} = \left\{ \left(\left(\theta_{\widetilde{\mathfrak{R}}}(\mathfrak{s})\right)^{\varpi}, \left(1 - \left(1 - \left(\eta_{\widetilde{\mathfrak{R}}}(\mathfrak{s})\right)\right)^{\varpi}\right), \left(1 - \left(1 - \left(\zeta_{\widetilde{\mathfrak{R}}}(\mathfrak{s})\right)\right)^{\varpi}\right)\right) \mid \mathfrak{s} \in \mathfrak{S}\right\} \text{ for } \varpi > 0 \tag{A5}$$

Following the principles, Definition 2 is expected to align with the following conditions[41]:

$$\widetilde{\mathfrak{R}}_1 \oplus \mathfrak{R}_2 = \widetilde{\mathfrak{R}}_2 \oplus \widetilde{\mathfrak{R}}_1 \tag{A6}$$

$$\widetilde{\mathfrak{R}}_1 \bigotimes \widetilde{\mathfrak{R}}_2 = \widetilde{\mathfrak{R}}_2 \bigotimes \widetilde{\mathfrak{R}}_1 \tag{A7}$$

$$\varpi\left(\widetilde{\mathfrak{R}}_1 \oplus \widetilde{\mathfrak{R}}_2\right) = \varpi\widetilde{\mathfrak{R}}_1 \oplus \varpi\widetilde{\mathfrak{R}}_2 \text{ for } \varpi > 0 \tag{A8}$$

$$\left(\widetilde{\mathfrak{R}}_1 \bigotimes \widetilde{\mathfrak{R}}_2\right)^{\varpi} = \widetilde{\mathfrak{R}}_1^{\varpi} \bigotimes \widetilde{\mathfrak{R}}_2^{\varpi} \text{ for } \varpi > 0 \tag{A9}$$

$$\varpi_1\widetilde{\mathfrak{R}} \oplus \varpi_2\widetilde{\mathfrak{R}} = (\varpi_1 + \varpi_2)\widetilde{\mathfrak{R}} \text{ for } \varpi_1, \varpi_2 > 0 \tag{A10}$$

$$\widetilde{\mathfrak{R}}^{\varpi_1} \int \widetilde{\mathfrak{R}}^{\varpi_2} = \widetilde{\mathfrak{R}}^{(\varpi_1 + \varpi_2)} \text{ for } \varpi_1, \varpi_2 > 0 \tag{A11}$$

Definition 3. Let us examine the existence of a PFS entity, specifically named $\widetilde{\mathfrak{R}}$, established within the universal set $\mathfrak{S}$, with its components outlined as $\widetilde{\mathfrak{R}} = \left(\theta_{\widetilde{\mathfrak{R}}}(\mathfrak{s}), \eta_{\widetilde{\mathfrak{R}}}(\mathfrak{s}), \zeta_{\widetilde{\mathfrak{R}}}(\mathfrak{s})\right)$. The computation of the score function denoted as $\mathcal{S}\left(\widetilde{\mathfrak{R}}\right)$, is performed using **Equation (**(A12)**)**:

$$\mathcal{S}\left(\widetilde{\mathfrak{R}}\right) = \frac{1}{3}\left(\left(\theta_{\widetilde{\mathfrak{R}}}(\mathfrak{s})\right) + \left(1 - \eta_{\widetilde{\mathfrak{R}}}(\mathfrak{s})\right) + \left(1 - \zeta_{\widetilde{\mathfrak{R}}}(\mathfrak{s})\right)\right);\ \mathcal{S}\left(\widetilde{\mathfrak{R}}\right) \in [0, 1] \tag{A12}$$

while the accuracy function denoted as $\mathcal{A}\left(\widetilde{\mathfrak{R}}\right)$, is determined by **Equation (**(A13)**)**:

$$\mathcal{A}\left(\widetilde{\mathfrak{R}}\right) = \theta_{\widetilde{\mathfrak{R}}}(\mathfrak{s}) + \zeta_{\widetilde{\mathfrak{R}}}(\mathfrak{s});\ \mathcal{A}\left(\widetilde{\mathfrak{R}}\right) \in [-1, 1] \tag{A13}$$

Definition 4. Consider the presence of two entities representing PFSs, specifically designated as $\widetilde{\mathfrak{R}}_1$ and $\widetilde{\mathfrak{R}}_2$, established within the universal set $\mathfrak{S}$. Their components are represented as $\widetilde{\mathfrak{R}}_1 = \left(\theta_{\widetilde{\mathfrak{R}}_1}(\mathfrak{s}), \eta_{\widetilde{\mathfrak{R}}_1}(\mathfrak{s}), \zeta_{\widetilde{\mathfrak{R}}_1}(\mathfrak{s})\right)$ and $\widetilde{\mathfrak{R}}_2 = \left(\theta_{\widetilde{\mathfrak{R}}_2}(\mathfrak{s}), \eta_{\widetilde{\mathfrak{R}}_2}(\mathfrak{s}), \zeta_{\widetilde{\mathfrak{R}}_2}(\mathfrak{s})\right)$. In the scenario where $\mathcal{S}\left(\widetilde{\mathfrak{R}}_a\right)$ and $\mathcal{A}\left(\widetilde{\mathfrak{R}}_a\right)$ indicate the score and accuracy functions of $\widetilde{\mathfrak{R}}_a$ $(a = 1, 2)$, ordinal relations can be determined as follows:

(i) If $\mathcal{S}\left(\widetilde{\mathfrak{R}}_1\right) > \mathcal{S}\left(\widetilde{\mathfrak{R}}_2\right)$, then $\widetilde{\mathfrak{R}}_1$ is greater than $\widetilde{\mathfrak{R}}_2$
(ii) If $\mathcal{S}\left(\widetilde{\mathfrak{R}}_1\right) = \mathcal{S}\left(\widetilde{\mathfrak{R}}_2\right)$ and $\mathcal{A}\left(\widetilde{\mathfrak{R}}_1\right) > \mathcal{A}\left(\widetilde{\mathfrak{R}}_2\right)$, then $\widetilde{\mathfrak{R}}_1$ is greater than $\widetilde{\mathfrak{R}}_2$
(iii) If $\mathcal{S}\left(\widetilde{\mathfrak{R}}_1\right) = \mathcal{S}\left(\widetilde{\mathfrak{R}}_2\right)$ and $\mathcal{A}\left(\widetilde{\mathfrak{R}}_1\right) = \mathcal{A}\left(\widetilde{\mathfrak{R}}_2\right)$, then $\widetilde{\mathfrak{R}}_1$ is equal to $\widetilde{\mathfrak{R}}_2$

Definition 5. Consider $\widetilde{\mathfrak{R}}_\gamma$, represented as $\widetilde{\mathfrak{R}}_\gamma = \left(\theta_{\widetilde{\mathfrak{R}}_\gamma}(\mathfrak{s}), \eta_{\widetilde{\mathfrak{R}}_\gamma}(\mathfrak{s}), \zeta_{\widetilde{\mathfrak{R}}_\gamma}(\mathfrak{s})\right)$, denoting a PFS $\left(\widetilde{\mathfrak{R}}_\gamma = \left(\widetilde{\mathfrak{R}}_1, \widetilde{\mathfrak{R}}_2, \ldots, \widetilde{\mathfrak{R}}_\beta\right)\right)$. At the same time, bring forth the associated weight vector $\omega = (\omega_1, \omega_2, \ldots, \omega_\gamma, \ldots, \omega_{\mathfrak{u}})$ for $\omega_\gamma\ \epsilon\ [0, 1]$ $(\gamma = \overline{1, \mathfrak{u}})$, with the restriction that $\sum_{\gamma=1}^{\mathfrak{u}} \omega_\gamma = 1$. In this context, the picture fuzzy weighted average (PFWA) aggregation operator (**Equation (**(A14)**)**) is defined by Ref. 41:

$$PFWA\left(\widetilde{\mathfrak{R}}_1, \widetilde{\mathfrak{R}}_2, \ldots, \widetilde{\mathfrak{R}}_\beta\right) = \oplus_{\gamma=1}^{\beta} \omega_\gamma \widetilde{\mathfrak{R}}_\gamma = \left\{ \left(\begin{array}{c} \left(1 - \prod_{\gamma=1}^{\beta}\left(1 - \theta_{\widetilde{\mathfrak{R}}_\gamma}(\mathfrak{s})\right)^{\omega_\gamma}\right), \\ \left(\prod_{\gamma=1}^{\beta}\left(\eta_{\widetilde{\mathfrak{R}}_\gamma}(\mathfrak{s})\right)^{\omega_\gamma}\right), \\ \left(\prod_{\gamma=1}^{\beta}\left(\zeta_{\widetilde{\mathfrak{R}}_\gamma}(\mathfrak{s})\right)^{\omega_\gamma}\right) \end{array} \right) \mid \mathfrak{s} \in \mathfrak{S} \right\} \tag{A14}$$

Appendix B: Notation

Indices and sets	
$\mathfrak{z} = 1, 2, \ldots, \mathfrak{Z}$	Index of cruise ports
$\mathfrak{y}^{(ql)} = 1, 2, \ldots, \mathfrak{Y}^{(ql)}$	Index of qualitative criteria
$\mathfrak{y}^{(qn)} = 1, 2, \ldots, \mathfrak{Y}^{(qn)}$	Index of quantitative criteria
$\mathfrak{x} = 1, 2, \ldots, \mathfrak{X}$	Index of experts
$X_{\mathfrak{z}} = \{X_1, X_2, \ldots, X_{\mathfrak{Z}}\}$	Set of cruise ports
$\Psi_{\mathfrak{y}^{(ql)}} = \left\{\Psi_1, \Psi_2, \ldots, \Psi_{\mathfrak{Y}^{(ql)}}\right\}$	Set of qualitative criteria
$\Psi_{\mathfrak{y}^{(qn)}} = \left\{\Psi_1, \Psi_2, \ldots, \Psi_{\mathfrak{Y}^{(qn)}}\right\}$	Set of quantitative criteria
$\Lambda^- \subseteq \Lambda$	Set of cost-based criteria
$\Lambda^+ \subseteq \Lambda$	Set of benefit-based criteria
$\Omega_{\mathfrak{x}} = \{\Omega_1, \Omega_2, \ldots, \Omega_{\mathfrak{X}}\}$	Set of experts
Parameters	
$\mathfrak{Z} \geq 2$	Number of cruise ports
$\mathfrak{Y}^{(ql)} \geq 2$	Number of qualitative criteria

$\mathfrak{Y}^{(qn)} \geq 2$	Number of quantitative criteria
$\mathfrak{X} \geq 2$	Number of experts
Variables	
$\mathcal{S}\left(\widetilde{\Omega}_{\mathfrak{x}}\right)(\mathfrak{x} \in \Omega)$	Score function value of the expert $\Omega_{\mathfrak{x}}$
$w_{\mathfrak{x}}(\mathfrak{x} \in \Omega)$	Significant level of the expert $\Omega_{\mathfrak{x}}$
$\widetilde{\mathfrak{P}}^{(\widetilde{\Omega}_{\mathfrak{x}})}_{\mathfrak{z}\mathfrak{y}^{(ql)}}(\mathfrak{x} \in \Omega,\ \mathfrak{z} \in X, \mathfrak{Y}^{(ql)} \in \Psi)$	PFS assessment of the cruise port $X_{\mathfrak{z}}$ depending on qualitative criteria $\Psi_{\mathfrak{y}^{(ql)}}$ provided by the expert $\Omega_{\mathfrak{x}}$
$\widetilde{\mathfrak{P}}_{\mathfrak{z}\mathfrak{y}^{(ql)}}(\mathfrak{z} \in X, \mathfrak{Y}^{(ql)} \in \Psi)$	Aggregated PFS assessment of the cruise port $X_{\mathfrak{z}}$ depending on qualitative criteria $\Psi_{\mathfrak{y}^{(ql)}}$
$\mathcal{S}\left(\widetilde{\mathfrak{P}}_{\mathfrak{z}\mathfrak{y}^{(ql)}}\right)(\mathfrak{z} \in X, \mathfrak{Y}^{(ql)} \in \Psi)$	Score function value of aggregated PFS assessment of the cruise port $X_{\mathfrak{z}}$ depending on qualitative criteria $\Psi_{\mathfrak{y}^{(ql)}}$
$\mathfrak{L}_{\mathfrak{z}\mathfrak{y}^{(qn)}}(\mathfrak{z} \in X, \mathfrak{Y}^{(qn)} \in \Psi)$	Value of the cruise port $X_{\mathfrak{z}}$ depending on quantitative criteria $\Psi_{\mathfrak{y}^{(qn)}}$

Indices and sets	
$\mathfrak{K}_{\mathfrak{z}\mathfrak{y}}(\mathfrak{z} \in X, \mathfrak{y} \in \Psi)$	Value of the cruise port $X_{\mathfrak{z}}$ depending on overall criteria $\Psi_{\mathfrak{y}}$
$\mathfrak{N}_{\mathfrak{z}\mathfrak{y}}(\ \mathfrak{z} \in X, \mathfrak{y} \in \Psi)$	Normalized value of the cruise port $X_{\mathfrak{z}}$ depending on overall criteria $\Psi_{\mathfrak{y}}$
$\Delta\mathfrak{N}_{\mathfrak{y}}(\mathfrak{y} \in \Psi)$	Criterion class vector value of the overall criteria $\Psi_{\mathfrak{y}}$
$tan\sigma_{\mathfrak{y}}\ (\mathfrak{y} \in \Psi)$	Slope vector value of the overall criteria $\Psi_{\mathfrak{y}}$
$E_{\mathfrak{y}}(\mathfrak{y} \in \Psi)$	Envelope vector value of the overall criteria $\Psi_{\mathfrak{y}}$
$ES_{\mathfrak{y}}(\mathfrak{y} \in \Psi)$	Envelope–slope ratio vector value of the overall criteria $\Psi_{\mathfrak{y}}$
$\mathbb{W}_{\mathfrak{y}}(\mathfrak{y} \in \Psi)$	Criteria weighting vector value of the overall criteria $\Psi_{\mathfrak{y}}$
$\mathfrak{I}_{\mathfrak{z}\mathfrak{y}}(\mathfrak{z} \in X, \mathfrak{y} \in \Psi)$	Normalized value of the cruise port $X_{\mathfrak{z}}$ depending on overall criteria $\Psi_{\mathfrak{y}}$
$\mathfrak{H}_{\mathfrak{z}\mathfrak{y}}(\mathfrak{z} \in X, \mathfrak{y} \in \Psi)$	Weighted value of the cruise port $X_{\mathfrak{z}}$ depending on overall criteria $\Psi_{\mathfrak{y}}$
$\mathfrak{F}_{\mathfrak{z}}(\mathfrak{z} \in X)$	Boundary proximity area value of the cruise port $X_{\mathfrak{z}}$
$\mathfrak{E}_{\mathfrak{z}\mathfrak{y}}(\mathfrak{z} \in X, \mathfrak{y} \in \Psi)$	Distance value of the cruise port $X_{\mathfrak{z}}$ depending on overall criteria $\Psi_{\mathfrak{y}}$
$\mathfrak{F}_{\mathfrak{z}}(\mathfrak{z} \in X)$	Ultimate distance value of the cruise port $X_{\mathfrak{z}}$

Abbreviation: PFS, picture fuzzy set.

Appendix C: The PFS–WENSLO–MABAC algorithm

This algorithm presents the steps of the PFS–WENSLO–MABAC hybrid method.

Algorithm	Steps
Input	In the context of a set of alternatives $X_{\mathfrak{z}} = \{X_1, X_2, \ldots, X_{\mathfrak{Z}}\}$, qualitative criteria $\Psi_{\mathfrak{y}^{(ql)}} = \left\{\Psi_1, \Psi_2, \ldots, \Psi_{\mathfrak{Y}^{(ql)}}\right\}$, quantitative criteria $\Psi_{\mathfrak{y}^{(qn)}} = \left\{\Psi_1, \Psi_2, \ldots, \Psi_{\mathfrak{Y}^{(qn)}}\right\}$, and a group of experts $\Omega_{\mathfrak{x}} = \{\Omega_1, \Omega_2, \ldots, \Omega_{\mathfrak{x}}\}$, the determination involves the weighting of the experts' matrix $\left(w = [w_{\mathfrak{x}}]_{\mathfrak{X}}\right)$, the weighting of the criteria matrix $\left(\mathbb{W}_{\mathfrak{y}} = [\mathbb{W}_{\mathfrak{y}}]_{\mathfrak{Y}}\right)$, and the ranking of alternatives matrix $\left(\mathfrak{D} = [\mathfrak{D}_{\mathfrak{z}}]_{\mathfrak{Z}}\right)$
Output	Assessing the sustainable tourism performance of cruise ports
Begin	
First stage	For determining the weights assigned to each expert

Step 1	Gather data pertaining to the significance levels attributed by the experts to LVs outlined in **Table 2**. Following this, convert LVs into PFSs
Step 2	Compute the score functions $\mathcal{S}\left(\widetilde{\Omega}_{\mathfrak{r}}\right)$ using **Equation** (1) for determining crisp values
Step 3	Compute the weighted matrix ($\mathrm{w} = [\mathrm{w}_{\mathfrak{r}}]_r$) for the invited experts using **Equation** (2)
Second stage	For calculating weights assigned to each criterion
Step 4	Assess each alternative by each expert based on each qualitative criterion using LVs illustrated in **Table 3**. Transform LVs into PFS. Then, obtain the initial decision matrices $\left(\widetilde{\mathfrak{P}}^{(\widetilde{\Omega}_{\mathfrak{r}})} = \left[\widetilde{\mathfrak{P}}_{\mathfrak{z}\mathfrak{y}^{(ql)}}^{(\widetilde{\Omega}_{\mathfrak{r}})}\right]_{\mathfrak{Z}x\mathfrak{Y}^{(ql)}}\right)$
Step 5	Calculate the aggregated decision matrix $\left(\widetilde{\mathfrak{P}} = \left[\widetilde{\mathfrak{P}}_{\mathfrak{z}\mathfrak{y}^{(ql)}}\right]_{\mathfrak{Z}x\mathfrak{Y}^{(ql)}}\right)$ with utilizing the PFWA aggregation operator $\left(PFWA\left(\widetilde{\mathfrak{P}}^{(1)}, \widetilde{\mathfrak{P}}^{(2)}, \ldots, \widetilde{\mathfrak{P}}^{(\mathfrak{X})}\right) = \oplus_{\mathfrak{r}=1}^{\mathfrak{X}} w_{\mathfrak{r}} \widetilde{\mathfrak{P}}^{(\mathfrak{r})}\right)$ (**Equation** (3))
Step 6	Compute the crisp initial decision matrix $\left(\mathfrak{P} = \left[\mathfrak{P}_{\mathfrak{z}\mathfrak{y}^{(ql)}}\right]_{\mathfrak{Z}x\mathfrak{Y}^{(ql)}}\right)$ for qualitative criteria using the score function (**Equation** (4))
Step 7	Construct the foundational decision matrix for overarching criteria $\left(\mathfrak{K} = [\mathfrak{K}_{\mathfrak{z}\mathfrak{y}}]_{\mathfrak{Z}x\mathfrak{Y}}\right)$ by through the integration of both qualitative and quantitative criteria
Step 8	Compute the normalization of the decision matrix $\left(\mathfrak{N} = [\mathfrak{N}_{\mathfrak{z}\mathfrak{y}}]_{\mathfrak{Z}x\mathfrak{Y}}\right)$ using **Equation** (5)
Step 9	Calculate the criterion class interval matrix $\left(\Delta\mathfrak{N}_{\mathfrak{y}} = [\Delta\mathfrak{N}_{\mathfrak{y}}]_{\mathfrak{Y}}\right)$ using **Equation** (6)
Step 10	Calculate the criterion slope matrix $\left(tan\sigma_{\mathfrak{y}} = [tan\sigma_{\mathfrak{y}}]_{\mathfrak{Y}}\right)$ using **Equation** (7)
Step 11	Calculate the criterion envelope matrix $\left(E_{\mathfrak{y}} = [E_{\mathfrak{y}}]_{\mathfrak{Y}}\right)$ using **Equation** (8)
Step 12	Calculate the criterion envelope–slope ratio matrix $\left(ES_{\mathfrak{y}} = [ES_{\mathfrak{y}}]_{\mathfrak{Y}}\right)$ using **Equation** (9)
Step 13	Calculate the criterion weighting matrix $\left(\mathbb{W}_{\mathfrak{y}} = [\mathbb{W}_{\mathfrak{y}}]_{\mathfrak{Y}}\right)$ using **Equation** (10)
Third stage	For determining rankings of the alternatives
Step 14	Calculate the normalized decision matrix $\left(\mathfrak{I} = [\mathfrak{I}_{\mathfrak{z}\mathfrak{y}}]_{\mathfrak{Z}x\mathfrak{Y}}\right)$ using **Equation** (11)
Step 15	Calculate the weighted decision matrix $\left(\mathfrak{H} = [\mathfrak{H}_{\mathfrak{z}\mathfrak{y}}]_{\mathfrak{Z}x\mathfrak{Y}}\right)$ using **Equation** (12)
Step 16	Calculate the BPA matrix $\left(\mathfrak{F} = [\mathfrak{F}_{\mathfrak{z}}]_{\mathfrak{Z}}\right)$ using **Equation** (13)
Step 17	Calculate the distance matrix $\left(\mathfrak{E} = [\mathfrak{E}_{\mathfrak{z}\mathfrak{y}}]_{\mathfrak{Z}x\mathfrak{Y}}\right)$ using **Equation** (14)
Step 18	Calculate the ultimate distance matrix $\left(\mathfrak{D} = [\mathfrak{D}_{\mathfrak{z}}]_{\mathfrak{Z}}\right)$ using **Equation** (15). The highest value of $\mathfrak{D}_{\mathfrak{z}}$ is the best option
End	

Abbreviations: BPA, boundary proximity area; LV, linguistic variable; MABAC, multi-attributive border approximation area comparison; PFS, picture fuzzy set; WENSLO, weights by envelope and slope.

Appendix D: The data for the number of cruise ships and the number of cruise passengers

Cruise ports	Number of cruise ships	Number of cruise passengers
Alanya cruise port (X_1)	18	19,119
Amasra cruise port (X_2)	19	14,359
Antalya cruise port (X_3)	24	33,825
Bodrum cruise port (X_4)	97	101,159
Bozcaada cruise port (X_5)	19	6311
Çanakkale cruise port (X_6)	40	19,672
Çeşme cruise port (X_7)	76	52,030
Dikili cruise port (X_8)	25	6530
Fethiye cruise port (X_9)	1	68
Göcek cruise port (X_{10})	5	691
Istanbul cruise port (X_{11})	219	392,382
İzmir cruise port (X_{12})	28	34,023
Kaş cruise port (X_{13})	4	1,777
Kuşadası cruise port (X_{14})	523	774,884
Marmaris cruise port (X_{15})	23	26,347
Samsun cruise port (X_{16})	2	1723
Sinop cruise port (X_{17})	12	9554
Trabzon cruise port (X_8)	18	13,311
Ünye cruise port (X_{19})	14	10,168