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RESEARCH ARTICLE

Instilling eco-friendly practices within the maritime industry: An intuitionistic fuzzy decision-analytic model for terminal operating system selection in green ports

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ABSTRACT

Green port operations require efficient and sustainable terminal management, supported by robust decision-making tools for selecting a terminal operating system (TOS). This research examines the complex process of selecting TOS in the context of green ports, aiming to identify the key criteria that influence the preference for TOS in facilitating port services. The study develops an intuitionistic fuzzy (IF) set-based hybrid decision-analytic model for TOS selection to enhance the overall performance of green ports. The IF–logarithmic decomposition of criteria importance (LODECI)–Aczel–Alsina Weighted Assessment (ALWAS) model was introduced. The IF–LODECI method was formulated for criterion weighting. It incorporated the maximum decomposition approach for robust weight stabilization. The IF–ALWAS method, based on the ALWAS method, was proposed to evaluate alternatives. The new hybrid decision-analytic model integrated Aczel–Alsina t-norm and t-conorm operations, with the IF–Aczel–Alsina weighted averaging operator as the final step. The application of the model was exemplified through a case study conducted at green ports in Türkiye, focusing on environmentally conscious criteria for TOS selection, involving six experts, 10 criteria, and five alternatives. The results revealed that "berth management and scheduling" was identified as the most significant criterion, while "Navis TOS" demonstrated the highest overall performance among the alternatives. Rigorous sensitivity analyses were conducted to validate the robustness of the proposed hybrid model and algorithm. This study presents a comprehensive decision-making framework for selecting TOS in green ports, bridging the gap between theoretical advancements and practical applications.

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1. Introduction

Maritime transportation stands as the preeminent modality for international trade, with ports representing an indispensable nexus within this framework. According to the European Environment Agency,[1] the transportation sector in Europe was responsible for 803 million tons of greenhouse gas (GHG) emissions in 2023, representing a 134.89% increase in emissions from maritime transportation since 1990. Moreover, the emissions in this sector have surged by 20% over the past decade.[2] While these figures highlight a significant regional increase, Europe's transportation emissions represent 9%–10% of global transport-related CO_2 emissions, indicating that other regions contribute more emissions. In addition, port operations, such as ship docking, cargo handling, and inland transportation, are an important source of GHGs; however, their specific contribution to total global emissions remains less accurately quantified.[3] In response to this escalating environmental concern, some initiatives have suggested evaluating route-based strategies to curtail emissions and fostering collaborative efforts between ports and the maritime sector for reducing GHG emissions.[4]

Within the sphere of industrial activities, ports contribute approximately 3% to global GHG emissions, underscoring their notable environmental footprint.[5] The emergence of "green ports" reflects a collective endeavor to mitigate environmental impacts within port facilities.[6] Green ports prioritize eco-friendly initiatives, encompassing the adoption of cleaner energy sources, the optimization of logistics to minimize emissions, and the incorporation of green technologies in port operations.[7]

Integral to the advancement of sustainable practices in the maritime domain, terminal operating systems (TOSs) assume a central role within the framework of green ports, aligning with the global imperative for environmental stewardship. TOS serves as a fundamental tool for optimizing the efficacy of port operations, facilitating the streamlined management of diverse processes encompassing cargo handling, vessel movements, and resource allocation.[8,9] Through the integration of TOS, green ports can leverage intelligent algorithms and real-time data analytics to enhance energy efficiency, reduce emissions, and mitigate environmental impact. The implementation of TOS enables the orchestration of activities, empowering ports to optimize routes, minimize idle times, and reduce fuel consumption, thereby contributing to a tangible reduction in the carbon footprint associated with maritime activities. Furthermore, TOS provides valuable insights into resource utilization, enabling green ports to make informed decisions on energy consumption, waste management, and overall sustainability strategies. In essence, the adoption of TOS represents a crucial step for green ports in their pursuit of environmental objectives, fostering operational efficiency and promoting eco-friendly practices within the maritime industry.[10]

By enhancing efficiency through optimization, TOS makes a significant contribution to port operations.[11] It provides a framework for coordinating and managing diverse operational processes.[12] TOS facilitates real-time monitoring and reporting of operations, affording decision-makers instantaneous access to critical data.[13] Through the application of intelligent algorithms and data analytics, TOS optimizes energy consumption.[14] It ensures the efficient utilization of resources, preventing wastage. Consequently, TOS facilitates the realization of more effective, efficient, and sustainable operations within port facilities.

Additionally, TOS makes significant contributions to sustainable port management. From an energy efficiency perspective, TOS contributes to sustainability goals by optimizing energy consumption in operations.[15–17] In terms of reducing environmental impacts, route optimization and high-efficiency processes minimize emissions and environmental effects. Regarding waste management, the implementation of intelligent inventory management optimizes material usage, thereby preventing waste. In the context of efficient resource utilization, TOS enhances the sustainability of operational processes.[18] From the standpoint of enhancing logistical efficiency, TOS reduces fuel consumption and makes transportation processes more sustainable.[19] In terms of reporting and monitoring, TOS enables informed decision-making by providing real-time information on environmental performance.[20]

The research gap lies in the limited studies focusing specifically on the selection of TOS tailored for green ports. The primary objective of this study is to address the TOS selection problem tailored for green ports. The literature has reported various types of TOS, and this research is conducted to determine the optimal TOS alternative in terms of sustainable port performance. The core motivation of the study is to develop a decision support system for the TOS selection process, specifically designed for use in green ports. Within this motivation, the TOS selection process was approached through a multicriteria decision-making (MCDM) framework.[21,22]

aiming to develop a group decision-making process. An intuitionistic fuzzy (IF) logic approach was adopted to eliminate uncertainties arising from expert perspectives and the structure of criteria in the TOS selection process.[23–32] A hybrid method was proposed, and an algorithm based on this hybrid model was formulated for the TOS selection problem. The proposed hybrid method was termed the IF–logarithmic decomposition of criteria importance (LODECI)–Aczel–Alsina weighted assessment (ALWAS) model. In this hybrid model, Aczel–Alsina t-norm and t-conorm operations were employed,[33,34] and the IF–Aczel–Alsina weighted averaging (IFAAWA) aggregation operator was applied.[35] The LODECI method,[36] developed based on IF sets, was proposed for criterion weighting purposes. The ALWAS method,[37] also developed with IF sets, was introduced for alternative ranking purposes.

1.1. Aims and contributions of the study

This research examines the selection process for TOS in green ports, with a particular focus on identifying the criteria that significantly influence the preference for TOS in delivering port services. The primary objective is to delineate these criteria and, based on them, develop a model for the optimal selection of TOS among alternatives. The study adopted an MCDM approach grounded in expert group decisions and IF sets. It aims to contribute to the academic domain by developing an algorithm and advocating for its use in enhancing the performance levels of green ports through strategic TOS selection.

In this study, the IF–LODECI–ALWAS hybrid model was introduced, rooted in IF sets. The LODECI method was employed for weighting criteria, adapted for IF sets to formulate the IF–LODECI method, which is recommended for criterion weighting. This method, relying on the maximum decomposition approach, provides a robust stabilization of weights, justifying its preference. In the evaluation of alternatives, the ALWAS method was chosen and modified for IF sets to establish the IF-ALWAS method, grounded in Aczel–Alsina nonlinear functions. Additionally, Aczel–Alsina t-norm and t-conorm operations were applied in the IF–LODECI–ALWAS hybrid model with the IFAAWA aggregation operator.

The detailed exposition of the IF–LODECI–ALWAS hybrid model included comprehensive information about IF sets, Aczel–Alsina t-norm and t-conorm operations, and a step-by-step elucidation of the entire model. To assess the robustness of the proposed hybrid model, various sensitivity analysis scenarios (SASs) were created, and the proposed algorithm was repeatedly applied. The findings from the SASs consistently support the robustness of the proposed hybrid method.

To showcase the applicability of the proposed model, a case study was conducted on green ports in Türkiye. The case study identified eco-centric criteria deemed important for TOS selection in green ports. These criteria were defined, and alternative TOS options were outlined. A professional expert group integral to the research provided its decisions, which were then subjected to the algorithm developed in the study.

This research significantly contributes to the field of green port management by focusing on the selection process of TOS in green ports. The primary contributions of this study are outlined as follows:

(i) Development of the IF–LODECI–ALWAS hybrid model: The model integrates the LODECI method for criterion weighting, specifically adapted for IF sets, as well as the ALWAS method for alternative evaluation, modified for IF sets. The application of Aczel–Alsina nonlinear functions, along with the use of Aczel–Alsina t-norm and t-conorm operations and the IFAAWA aggregation operator, enhances the model's accuracy and flexibility. Based on this model, a practical algorithm is presented to assist green port managers in selecting TOS according to the identified criteria, enhancing overall green port performance.

(ii) Robustness verification through sensitivity analysis: The research employed various SASs to rigorously test and validate the robustness of the proposed IF–LODECI–ALWAS hybrid model and the associated algorithm. The consistent results from the sensitivity analysis findings reinforce the reliability of the proposed decision-making framework.

(ii) Application in a real-life context: The research systematically identified and elucidated the key criteria that play a pivotal role in the preference for TOS used in delivering port services within the context of green ports. These criteria formed the foundation for the development of a robust decision-making model, which was subsequently applied in a real-world setting through a case study conducted on green ports in Türkiye. This application demonstrated the feasibility and practicality of the proposed approach, providing valuable insights for practitioners in the port sector.

(iv) Insights into green port management: The research concludes with the dissemination of specific results related to TOS selection in green ports. Furthermore, it provides actionable insights and recommendations tailored for green port managers, helping them make informed decisions that align with environmental considerations.

In essence, this research advances the understanding of sustainable practices in maritime operations, particularly in the context of green port management, and provides practical tools for both industry professionals and academics.

1.2. Study organization

This paper is structured into five main sections. In Section 2, the methodological framework is elucidated, encompassing those for the IF–LODECI–ALWAS model, thereby providing a basis for formulating an algorithm. Section 3 involves the application of a case study, where the developed algorithm was implemented based on the constructed case study, presenting all procedural steps. Section 4 outlines the results and implications, beginning with the presentation of case study application results, followed by the implementation of SASs. Subsequently, research and managerial implications are provided. Section 5 serves as the conclusion, where research limitations and recommendations for future research are presented.

2. Methodological framework

In this research, the novel IF–LODECI–ALWAS hybrid model was developed. The methodology for developing this hybrid model begins with the presentation of preliminaries related to IF sets. Subsequently, the Aczel–Alsina t-norm and t-conorm operations were explained, followed by the elucidation of the IFAAWA aggregation operator. The step-by-step procedures of IF-LODECI-ALWAS were then presented. This hybrid model comprised three distinct stages. In the first stage, the significance levels of experts in the decision-making process were calculated. In the second stage, criteria weights were determined using the IF–LODECI method. In the third stage, alternatives were weighed using the IF–ALWAS method to obtain rankings. The methodological flow for the IF–LODECI–ALWAS method is illustrated in **Figure 1**.

2.1. Algorithm of the intuitionistic fuzzy–logarithmic decomposition of criteria importance–Aczel–Alsina weighted assessment hybrid model

The primary aim of this algorithm is to illustrate the IF–LODECI–ALWAS hybrid model, constructed through the utilization of the IFAAWA aggregation operator and the integration of Aczel–Alsina t-norm and t-conorm operations. Preliminaries of IFs[38] are provided in **Appendix A1**. The Aczel–Alsina operations [39] in IFs are given in **Appendix A2**. The IFAAWA aggregation operator is provided in **Appendix A3**.

Consider $(T_e) = \{T_1, T_2, \ldots, T_p\}$ $(e= 1, 2, \ldots, p)$ as alternatives, $(A_f) = \{A_1, A_2, \ldots, A_q\}$ ($f= 1, 2, \ldots, q)$ as the criteria, and $(E_g) = \{E_1, E_2, \ldots, E_r\}$ $(g= 1, 2, \ldots, r)$ as experts in computing the matrix of expert significance $\left(s = [s_g]_r\right)$, weighting of the criteria matrix $\left(w = [w_f]_q\right)$, and ranking of the alternatives matrix $\left(N = [N_e]_p\right)$ were the inputs for the algorithm. The output is the ranking of the alternatives. The procedural steps of the proposed model are delineated as follows:

(ii) Step 1: The evaluation of expert significance was conducted by referencing the linguistic variables (LV) outlined in **Table 1**.[40] Subsequent to this evaluation, LVs were transformed into IF sets, and significance levels were determined for each expert within the IF sets framework.

(ii) Step 2: The matrix of expert significance $\left(s=[s_g]_r\right)$ was calculated employing **Equation** (1)

$$s_g = \frac{\beta_{\widetilde{Y}_g}(z)\left(2 - \beta_{\widetilde{Y}_g}(z) - ?_{\widetilde{Y}_g}(z)\right)}{\sum_{g=1}^{r}\left(\beta_{\widetilde{Y}_g}(z)\left(2 - \beta_{\widetilde{Y}_g}(z) - ?_{\widetilde{Y}_g}(z)\right)\right)}; \quad (g = 1, 2, ..., r).h \tag{1}$$

(ii)Step 3: Each alternative (T_e) underwent assessment by each expert (E_g) concerning each criterion (A_f), utilizing LVs outlined in **Table 2**.[41] After this evaluation, LVs were transformed into corresponding IF sets (**Table 2**). This process resulted in the formation of initial decision matrices $\left(\widetilde{B}^{(E_g)} = \left[\widetilde{B}_{ef}^{(E_g)}\right]_{pxq}\right)$, where

$$\widetilde{Y}_{\widetilde{B}_{ef}^{(E_g)}} = \left(\beta y_{\widetilde{Y}_{\widetilde{B}_{ef}^{(E_g)}}}(z), ?_{\widetilde{Y}_{\widetilde{B}_{ef}^{(E_g)}}}(z)\right) \quad (e= 1, 2, \ldots, p;\ f= 1, 2, \ldots, q;\ g= 1, 2, \ldots, r) \tag{2}$$

(iv) Step 4: Utilizing the IFAAWA aggregation operator, as defined in **Equation** (3), the aggregated decision-matrix $\left(\widetilde{B} = \left[\widetilde{B}_{ef}\right]_{pxq}\right)$ was calculated.

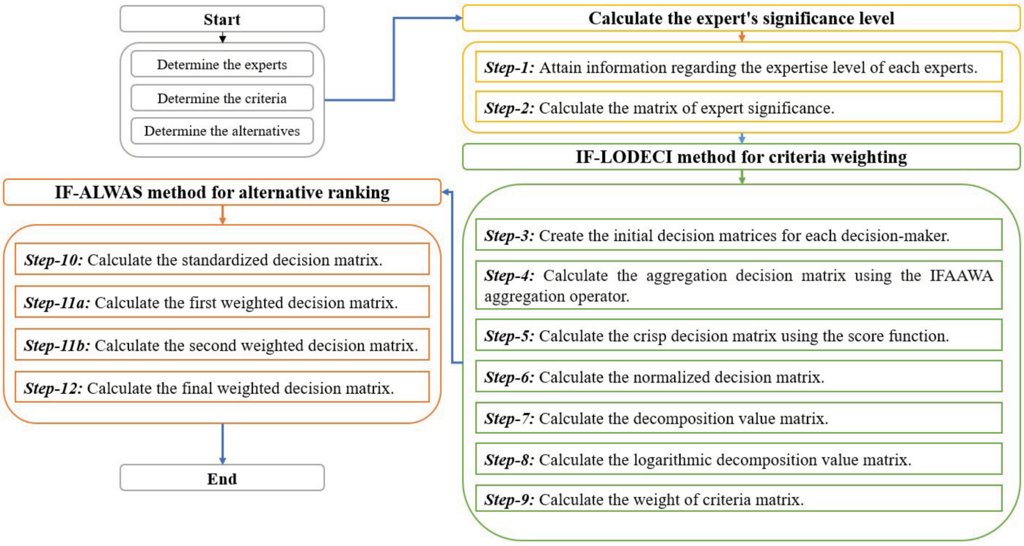

Figure 1. Methodological flowchart
Abbreviations: ALWAS: Aczel–Alsina weighted assessment; IF: Intuitionistic fuzzy; IFAAWA: IF–Aczel–Alsina weighted averaging; LODECI: Logarithmic decomposition of criteria importance.

Table 1. Linguistic variables for determining the significance of experts

Expertise	**IF sets**
Outstanding (O)	(1.00, 0.00)
Exceeds expectations (EE)	(0.90, 0.05)
Meet expectations (ME)	(0.70, 0.20)
Moderate (M)	(0.60, 0.30)
Needs improvements (NI)	(0.30, 0.60)
Unacceptable (U)	(0.10, 0.80)

Abbreviation: IF: Intuitionistic fuzzy.

Table 2. Linguistic variables for evaluations.

Linguistic variables	**IF sets**
Very important (VI)	(0.88,0.08)
Important (I)	(0.75,0.20)
Medium (M)	(0.50,0.45)
Unimportant (UI)	(0.35,0.60)
Very unimportant (VU)	(0.08,0.88)

Abbreviation: IF: Intuitionistic fuzzy.

$$IFAAWA\left(\widetilde{B}^{(E_1)},\widetilde{B}^{(E_2)},\ldots,\widetilde{B}^{(E_r)}\right)=$$

$$\oplus_{g\,=\,1}^{r} s_g \widetilde{B}^{\left(E_g\right)} ==$$

$$\left(\left(1-e^{-\left(\sum_{g=1}^{r} s_g\left(-log\left(1-\beta_{\widetilde{Y}_{\widetilde{B}^{(E_g)}}}(z)\right)\right)^{\theta}\right)^{1/\theta}}\right), \quad (3)$$

$$\left(e^{-\left(\sum_{g=1}^{r} s_g\left(-log\left(?_{\widetilde{Y}_{\widetilde{B}^{(E_g)}}}(z)\right)\right)^{\theta}\right)^{1/\theta}}\right),$$

where the vector representing the significance of experts is denoted as $s_g=(s_1,s_2,\ldots,s_r)$, with $s_g\ \varepsilon\ [0,1]$, $\sum_{g\,=\,1}^{r} s_g=1$ and $\theta>0$.

(v) Step 5: Employing the score function $\left(S\left(\widetilde{B}_{ef}\right)\right)$, as presented in **Equation** (4), the crisp values were computed. Subsequently, the definitive decision matrix $\left(C=[C_{ef}]_{pxq}\right)$ was derived.

$$C_{ef}=S\left(\widetilde{B}_{ef}\right)=\left(\beta_{\widetilde{B}_{ef}}(z)-\gamma_{\widetilde{B}_{ef}}(z)\right); \quad (4)$$
$$(e=1,2,\ldots,p;\ f=1,2,\ldots,q).$$

(vi) Step 6: **Equation** (5) was used to compute the normalized decision matrix $\left(D{=}[D_{ef}]_{pxq}\right)$:

$$D_{ef}{=}\left(\begin{array}{l} \frac{C_{ef}}{{C_f}^{max}}\ if\ f{\in}benefit\ criteria \\ \frac{{C_f}^{min}}{C_{ef}}\ if\ f{\in}cost\ criteria \end{array}\right); \quad (e=1,2,\ldots,p;\ f=1,2,\ldots,q). \tag{5}$$

(vii) Step 7: **Equation** (6) was used to compute the decomposition value matrix $\left(F{=}[F_{ef}]_{pxq}\right)$:

$$F_{ef} = max\left\{|D_{ef}-D_{yf}|\right\}; \quad (e,y=1,2,\ldots,p \mid e?y; \quad f=1,2,\ldots,q. \tag{6}$$

(viii) Step 8: **Equation** (7) was used to compute the logarithmic decomposition value matrix $\left(G{=}[G_f]_q\right)$:

$$G_f{=}ln\left(1{+}\frac{\sum_{e\,=\,1}^{p}F_{ef}}{p}\right);\ (f=1,2,\ldots,q). \tag{7}$$

(ix) Step 9: **Equation** (8) was used to compute the weighting of the criteria matrix $\left(w=[w_f]_q\right)$:

$$w_f=\frac{G_f}{\sum_{l\,=\,1}^{q}G_l};\ (f=1,2,\ldots,q). \tag{8}$$

(x) Step 10: The crisp decision matrix $C=[C_{ef}]_{pxq}$ from Step 5 was employed as the initial decision matrix. The standardized decision matrix $\left(K=[K_{ef}]_{pxq}\right)$ was obtained as

$$K_{ef}{=}\left\{\begin{array}{l} \frac{C_{ef}}{max_{1=e=p}C_{ef}};\ if\ f{\in}benefit\ criteria \\ -\frac{C_{ef}}{max_{1=e=p}C_{ef}}{+}max_{1=e=p}\left(\frac{C_{ef}}{max_{1=e=p}C_{ef}}\right)+ \\ min_{1=e=p}\left(\frac{C_{ef}}{max_{1=e=p}C_{ef}}\right);\ if\ f{\in}cost\ criteria \end{array}\right\}; \quad (e=1,2,\ldots,p;\ f=1,2,\ldots,q). \tag{9}$$

(xi) Step 11a: The first weighted decision matrix $\left(L{=}[L_e]_p\right)$ was computed utilizing the Aczel–Alsina weighted arithmetic mean strategy and by applying **Equation** (10). The corresponding weight vector was identified as $w_f=(w_1,w_2,\ldots,w_q)$, where $w_f\ \varepsilon\ [0,1]$, $\sum_{f\,=\,1}^{q}w_f=1$, and $\theta>0$.

$$L_e{=}\sum_{f\,=1}^{q}K_{ef}\left(1{-}e^{-\left(\sum_{f=1}^{q}w_f\left(-ln\left(1-\frac{K_{ef}}{\sum_{f=1}^{q}K_{ef}}\right)\right)^{\theta}\right)^{1/\theta}}\right); \quad (e{=}\ 1,2,\ldots,p). \tag{10}$$

(xii) Step 11b: The second weighted decision matrix $\left(M=[M_e]_p\right)$ was computed utilizing the Aczel–Alsina weighted geometric mean strategy and by applying **Equation** (11). The corresponding weight vector was identified as $w_f=(w_1,w_2,\ldots,w_q)$, where $w_f\ \varepsilon\ [0,1]$, $\sum_{f=1}^{q}w_f{=}\ 1$, and $\theta{>}\ 0$.

$$M_e{=}\sum_{f=1}^{q}K_{ef}\left(e^{-\left(\sum_{f=1}^{q}w_f\left(-ln\left(\frac{K_{ef}}{\sum_{f=1}^{q}K_{ef}}\right)\right)^{\theta}\right)^{1/\theta}}\right); \quad (e{=}\ 1,2,\ldots,p). \tag{11}$$

(xiii) Step 12: **Equation** (12) was used to compute the final weighted matrix $\left(N=[N_e]_p\right)$ for alternative ranking with $?{>}\ 0$ and $1\geq\mu\geq0$ as:

$$N_e{=}\frac{L_e{+}M_e}{1{+}\left(\mu\left(\frac{1-\frac{L_e}{L_e+M_e}}{\frac{L_e}{L_e+M_e}}\right)^{?}+(1{-}\mu)\left(\frac{1-\frac{M_e}{L_e+M_e}}{\frac{M_e}{L_e+M_e}}\right)^{?}\right)^{1/?}}; \quad (e{=}\ 1,2,\ldots,p). \tag{12}$$

where the optimal alternative ranking is the highest value of N_e.

3. Case study

In this study, an IF–LODECI–ALWAS hybrid model and associated algorithm were proposed as a decision support system for the TOS selection process in green ports. A case study was conducted focusing on the green port (Mersin Port) in Türkiye to test the applicability of this hybrid model. Initially, an expert group was formed for the TOS selection, consisting of six experts. Subsequently, TOS selection criteria were identified through a literature review and expert consultations, resulting in the determination of 10 TOS selection criteria. Following this, TOS alternatives were defined, with a total of five alternatives being included in the decision model. In this case study, the expert group, criteria, and alternatives were utilized to construct a decision model, and the IF–LODECI–ALWAS hybrid model was applied. After explaining the components of the decision model, the algorithm was employed to execute the decision model, and the results obtained were systematically shared step by step.

3.1. Experts, criteria, and terminal operating systems for green port

3.1.1. Expert identification

To facilitate informed decisions in the TOS selection process, a specialized panel should be constituted, comprising individuals with expertise in both planning and implementation. In the empirical investigation of TOS selection through a case study, meticulous attention was devoted to the composition of the expert group, with a deliberate intention to amalgamate diverse viewpoints. To accomplish this objective, the expert panel was curated to include not only high-level decision-makers, such as top-tier executives, but also field personnel actively engaged in implementation. The categorization of decision-makers considered organizational hierarchical levels and the accumulated years of professional experience, ensuring a comprehensive representation of perspectives within the group. The occupational stratification of the expert panel is delineated in **Table 3**.

3.1.2. Criteria identification

The determination of criteria in the TOS selection process is a crucial aspect of achieving sustainable port performance. In this process, two fundamental approaches were recognized for criteria determination. The first fundamental approach is the process of determining criteria based on a literature review. The second approach involves determining criteria based on expert opinions.

In this research, these two approaches were combined. Initially, the TOS selection criteria identified in the literature were examined,[18] and these criteria were evaluated according to the expectations of green ports. Subsequently, the final criteria were established by obtaining expert opinions. Within the scope of the study, 10 criteria were identified for inclusion in the decision model. These criteria are as follows:

(i) Yard management (A_1) plays a pivotal role in contemporary supply chain logistics, employing a comprehensive approach to efficiently oversee the storage, movement, and organization of goods within a designated space.[42] A fundamental aspect of effective yard management involves designing a customizable yard layout tailored to the unique requirements of multiple terminals or yards, accommodating varied traffic patterns and routes.[43] This necessitates the incorporation of advanced technologies capable of delivering real-time visibility for each unit at all relevant locations, ensuring a detailed comprehension of the movement and status of assets within the yard. Furthermore, a crucial function of yard management systems involves optimizing space utilization and organizing container freight station operations.

(ii) Berth management and scheduling (A_2) assumes a central role in optimizing the judicious usage of berths, providing insights into waterway activities, and establishing an exhaustive database of vessel-related information.[44] An effective berth management and scheduling feature is imperative for terminals to manage the arrival and departure of vessels systematically and punctually.[45] This entails strategic planning and allocation of berths for incoming vessels, considering variables such as vessel dimensions, cargo specifications, and various operational constraints.

(iii) Port and vessel operations (A_3) encompass various factors influencing processes related to port operations and vessel activities. Evaluation within this criterion extends to loading, unloading, storage, and other port operations. It assesses the features that TOS must possess to effectively manage containers and other cargo types.[18] Within this criterion, it is imperative for TOS to endorse and implement robust security measures. The consideration of this criterion in TOS selection is attributable to its capacity to optimize operational processes and enhance security.

(iv) Gate management (A_4): Facilitating the coordinated movement of truck and rail traffic within port facilities, gate management plays a central role in optimizing the operational flow.[46] It is a significant criterion in the selection of TOS, encompassing functionalities related to the efficient administration of entry and exit points within a terminal. This criterion facilitates the controlled entry and exit of transportation units through efficient gate management, enabling appointment planning for both incoming and outgoing shipments.[47] Effective gate management optimizes vehicle queues to reduce waiting times; supports report generation for auditing, compliance, and operational analysis; and maintains a consistent flow of information across terminal operations, thereby fostering seamless integration with other TOS modules.

(v) Customer relationship management (A_5) is a significant criterion in the TOS selection, encompassing functionalities focused on developing and managing relationships with terminal customers. This criterion pertains to features such as customer portals, communication channels, and notifications, aiming at timely and transparent information exchange. It includes flexible planning, personalized reporting, and tailored solutions to meet specific customer needs. Additionally, this criterion focuses on contributing to customer satisfaction by providing a fast and effective resolution process.[48] Therefore, it constitutes one of the TOS selection criteria for green ports.

Table 3. The experts identified for the TOS selection process.

Experts	Experience (years)	Significance	Professions
E_1	13	EE	Trade development manager
E_2	18	O	Port operations director
E_3	18	M	Port operations team leader
E_4	18	O	Chief information officer
E_5	14	ME	Customer relationship manager
E_6	15	ME	Customs and customer services manager

Abbreviations: EE: Exceeds expectations; M: Medium; ME: Meet expectations; O: Outstanding; TOS: Terminal operating system.

(vi) Communications (A_6) signifies the system's capacity to facilitate effective and uninterrupted communication both within the terminal and with external stakeholders. It encompasses features, such as messaging systems, internal notifications, and collaborative platforms to ensure a consistent flow of information.[49] This criterion underscores the need for the system to support interfaces and protocols for seamless information exchange with external entities, indicating its role in enabling coordinated and transparent operations. Additionally, it emphasizes the importance of keeping all stakeholders informed about critical events, schedule changes, and operational disruptions to ensure operational awareness. Furthermore, it highlights the importance of integrating with email systems, instant messaging applications, and collaboration tools to facilitate efficient communication workflows.

(vii) Vehicle and equipment management (A_7) is a criterion encompassing functionalities that focus on the efficient and optimized utilization of vehicles and equipment within a terminal. This criterion involves real-time monitoring of the locations, statuses, and movements of terminal assets to ensure visibility and control.[50] It includes monitoring weight limits, adherence to safety regulations, and ensuring that equipment meets necessary standards through intelligent assignment and scheduling to prevent congestion, enhance efficiency, and meet demand fluctuations.[51] Furthermore, the primary objective of this criterion is to enable terminal operators to maximize the benefits of the system while managing their assets. In this context, this criterion stands among the selection criteria for TOS, particularly in the context of green ports.

(viii) Decarbonization management (A_8) represents system capabilities designed to manage and optimize the reduction of carbon emissions in terminal operations. This criterion emphasizes the optimization of equipment operations, the utilization of energy-saving technologies (e.g., solar panels, wind turbines, and other renewable sources that can power terminal equipment and facilities), and the implementation of measures to reduce overall energy consumption.[52] It supports the assessment of environmental impact and compliance with regulatory requirements while providing opportunities for identifying areas for improvement and implementing targeted emission reduction strategies.[53] Thus, it is evaluated as a TOS selection criterion in terms of its contribution to and optimization of carbon emissions reduction in terminal operations.

(ix) Performance analysis (A_9) encompasses functionalities within the system that allow for the comprehensive analysis and evaluation of terminal operations.[18] This criterion involves analyzing the performance of various processes, identifying bottlenecks, and facilitating streamlined workflows to increase productivity. The functionalities of performance analysis enable the optimization of allocation and planning by helping to identify underutilized or overutilized resources. Emphasizing the monitoring of operational speed and volume to ensure the terminal operates at maximum capacity, this criterion highlights the use of data-driven decision-making to optimize processes and enhance overall performance. Additionally, it contributes to strategic planning and the continuous improvement of terminal operations.

(x) Data analytics and reporting (A_{10}) entails the functionalities and capabilities within the system related to the comprehensive analysis of data and the generation of understandable reports.[54] This criterion signifies the application of statistical methods, machine learning algorithms, and other analytical techniques to gain deeper insights into terminal operations, enabling terminal operators to assess the efficiency of various processes, identify areas for improvement, and track progress over time. Additionally, it aids in proactive decision-making and optimizing terminal operations. Focusing on the system's ability to leverage data for in-depth analysis, generate meaningful reports, and support informed decision-making within terminal operations, this criterion enables the selection of TOS that excel in these areas.

3.1.3. Port operation system identification

Following an examination focused on TOS employed in green ports in Türkiye, the findings revealed the existence of five distinct TOS utilized in the country. Among these TOS platforms are SolonPort, GullsEye, Navis, OSCAR, and OPUS. Descriptions pertaining to each of these TOS are articulated as follows:

(i) SolonPort TOS (T_1): The SolonPort TOS software emerges as a pioneering integration in the port industry, strategically crafted to seamlessly integrate with diverse equipment in alignment with the prevalent adoption of advanced technologies. Distinguished by its capacity to deliver peak operational efficiency, the software optimizes workforce utilization through its intuitive features and meticulously designed operational workflows. Specifically tailored processes catering to containers, mixed cargo, roll-on/roll-off, and liquid terminals were methodically developed, supported by advanced-scenario capabilities. SolonPort offers a comprehensive platform for managing and monitoring terminals, accommodating diverse requirements within a single framework. Harnessing cutting-edge technology, users gain the ability to proficiently manage the entirety of port operations. Particularly noteworthy are the optimization structures and algorithms ingrained in SolonPort, representing the zenith of sophistication to ensure minimal disruptions and maximal performance. This unique software solution stands at the vanguard of the port industry, ushering in unparalleled efficiency and adaptability within a landscape characterized by relentless technological advancement.[55]

(ii) GullsEye TOS (T_2): The GullsEye TOS emerges as a comprehensive TOS meticulously engineered to streamline services across container, roll-on/roll-off, etc. The system's optimization and workflow modules play a pivotal role in augmenting productivity while mitigating operational costs. GullsEye introduces feature-rich dashboards accessible through both mobile devices and web interfaces, furnishing real-time access to statistical insights and key performance indicators for informed decision-making. Furthermore, the system empowers clients to oversee and manage operations remotely through web and mobile applications, presenting a self-service paradigm. The seamless integration of GullsEye with Enterprise Resource Planning (ERP) systems adds substantial value, underscoring a holistic approach to comprehending and overseeing terminal operations. Drawing upon extensive expertise in software development, 3D virtualization, and supply chain optimization, GullsEye is an intricate and effective solution within the domain of TOSs.[56]

(iii) Navis TOS (T_3): At the core of terminal operations, the Navis TOS is a remarkably robust system, adeptly configured to oversee a diverse spectrum of cargo types. Its adaptability extends to accommodating flexible work environments, facilitating the centralized administration of multiple sites, terminals, and subterminals within a consolidated database. Providing a cohesive, real-time operational perspective, Navis empowers stakeholders to promptly make well-informed decisions. The system upholds a high standard of security through bank-level encryption and deploys intelligent technology, positioning it as a pliable and scalable solution. Beyond fortifying internal operations, Navis facilitates the seamless dissemination of cargo information throughout the supply chain, transcending conventional port demarcations. These characteristics augment business expansion for ports by heightening visibility and competitiveness in an industry distinguished by exacting standards. Ports leveraging Navis embody adaptability, enabling them to contend effectively with major entities in the global maritime sector and emerge triumphant.[57]

(iv) OSCAR TOS (T_4): The OSCAR TOS presents a contemporary, user-friendly, and cost-effective TOS. It provides extensive support for real-time control over both land and maritime operations. This advanced TOS excels in optimizing daily terminal activities, demonstrating ease of adaptability to diverse organizational structures and operational procedures. Its user-friendly and comprehensive interface ensures rapid adoption by terminal teams, facilitating seamless integration into existing workflows. Remarkably, its lightweight yet robust technical architecture guarantees exceptional system availability without necessitating supplementary information technology resources. In essence, it manifests as a versatile and efficient solution adept at addressing the distinctive operational requirements of smaller and medium-sized terminals on a global scale. [58]

(v) OPUS TOS (T_5): The OPUS TOS is a comprehensive solution tailored to the operational intricacies of container terminals, encompassing functions, such as loading and unloading, classification, storage, and adaptability to evolving terminal requirements. In response to the escalating volume of maritime transportation, carriers have forged strategic alliances and increased vessel sizes, prompting terminals to pursue expansion and automation to accommodate these developments. The imperative to enhance infrastructure, automate equipment, and improve services aligns with the expanding scope of terminal information sharing. Notably, achieving high productivity is paramount in maintaining vessel punctuality. The OPUS TOS addresses these challenges by providing flexible processing capabilities that facilitate the expansion of terminal businesses and associated services. Its architectural features are purposefully designed to accommodate modular units, ensuring adaptability to specific business modules and fostering operational efficiency within the dynamic landscape of maritime terminal operations.[59]

3.2. Terminal operating system selection using the proposed fuzzy–logarithmic decomposition of criteria importance–Aczel–Alsina weighted assessment hybrid model

All steps within the scope of the algorithm developed for the IF–LODECI–ALWAS hybrid model were sequentially implemented as follows:
(i) Step 1: LVs were obtained based on Table 1. Next, these LVs were converted into IF sets (**Table S1**).
(ii) Step 2: Using **Equation** (1), the matrix of expert significance $\left(s{=}[s_g]_r\right)$ was calculated (**Table 4**).
(iii) Step 3: Based on **Table 2**, each expert evaluated each TOS with LVs for each criterion. The evaluations of the experts are presented in **Table S2**. LVs were transformed into IF sets (**Table S3**). Then, the initial decision matrices $\left(\widetilde{B}^{(E_g)}{=}\left[\widetilde{B}_{ef}^{(E_g)}\right]_{5x10}\right)$ were obtained.
(iv) Step 4: The aggregated decision matrix $\left(\widetilde{B}=\left[\widetilde{B}_{ef}\right]_{5x10}\right)$ (**Table S4**) was computed using the IFAAWA aggregation operator (**Equation [2]**) and $s=[s_g]_r$ matrix ($\theta=1$).
(v) Step 5: The crisp decision-matrix $\left(C={[C_{ef}]}_{5x10}\right)$ (**Table S5**) was computed using the score function $\left(S\left(\widetilde{B}_{ef}\right)\right)$ (**Equation [3]**).
(vi) Step 6: The normalized decision-matrix $\left(D=[D_{ef}]_{5x10}\right)$ (**Table S6**) was calculated using **Equation** (5).
(vii) Step 7: The decomposition value matrix $\left(F=[F_{ef}]_{5x10}\right)$ (**Table S7**) was calculated using **Equation** (6).
(viii) Step 8: The logarithmic decomposition value matrix $\left(G=[G_f]_q\right)$ (**Table S8**) was calculated using **Equation** (7).
(ix) Step 9: The weights of the criteria matrix $\left(w=[w_f]_q\right)$ (**Table 5**) was calculated using **Equation** (8).
(x) Step 10: The standardized decision matrix $\left(K=[K_{ef}]_{5x10}\right)$ (**Table S9**) was calculated using **Equation** (9).
(xi) Step 11a: The first weighted decision matrix $\left(L=[L_e]_p\right)$ (**Table S10**) was computed utilizing the Aczel–Alsina weighted arithmetic mean strategy (**Equation [9]**) and the corresponding weight vector ($w_f=(w_1,w_2,\ldots,w_{10})$).
(xiii) Step 11b: The second weighted decision matrix $\left(M=[M_e]_p\right)$ (**Table S11**) was computed utilizing the Aczel–Alsina weighted geometric mean strategy (**Equation [10]**) and the corresponding weight vector ($w_f=(w_1,w_2,\ldots,w_{10})$).
(xiii) Step 12: The final weighted matrix $\left(N=[N_e]_p\right)$ (**Table 6**) for the alternative ranking was calculated using **Equation** (12) with ? = 1 and $\mu=0.5$.

4. Results and discussion

This research addressed the TOS selection problem to enhance sustainable port performance. An IF–LODECI–ALWAS hybrid model was developed and applied in a case study of the green ports in Türkiye. The results obtained were evaluated from two main perspectives. The first perspective pertains to the weights of the criteria, and the second pertains to the ranking of alternative TOS in terms of sustainability. The weight ranking results for the criteria are as follows: "berth management and scheduling (A_2)" > "decarbonization management (A_8)" > "customer relationship management (A_5)" > "yard management (A_1)" > "communications (A_6)" > "gate management (A_4)" > "data analytics and reporting (A_{10})" > "performance analysis (A_9)" > "port and vessel operations (A_3)" > "vehicle and equipment management (A_7)." According to these results, A_2 was the most crucial criterion, indicating that quay management and planning play a paramount role in the TOS selection for sustainable port performance. The criterion with the lowest importance level was A_7, suggesting that vehicle and equipment management is relatively less significant in TOS selection compared to other criteria.

The ranking of alternative TOS is as follows: "Navis TOS (T_3)" > "GullsEye TOS (T_2)" > "OPUS TOS (T_5)" > "SolonPort TOS (T_1)" >

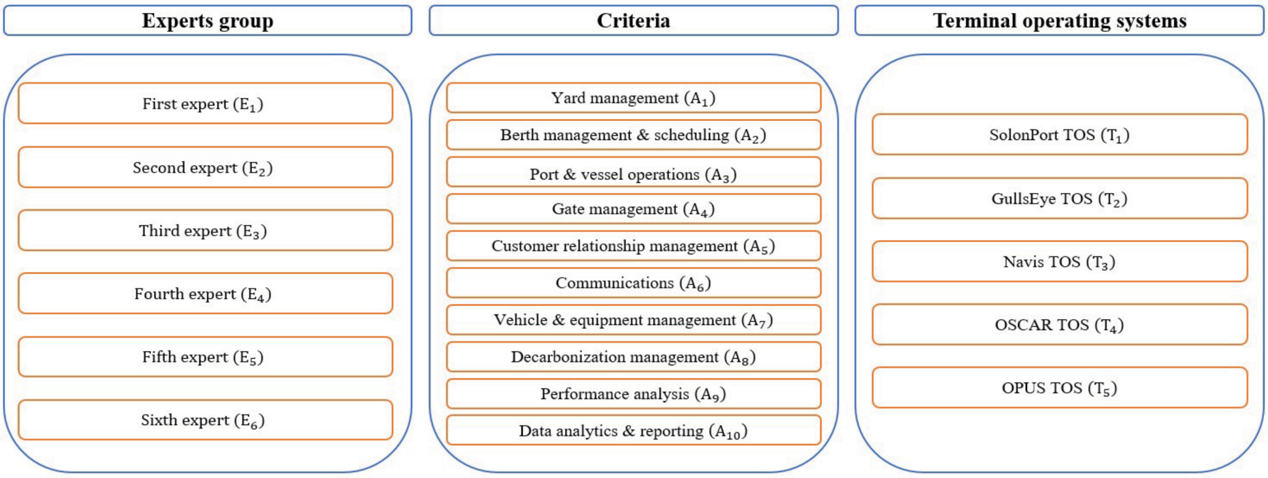

Figure 2. Decision model components

Table 4. Matrix of expert significance $\left(s{=}[s_g]_r\right)$

Experts	E_1	E_2	E_3	E_4	E_5	E_6
Significance (s_g)	0.1837	0.1944	0.1283	0.1944	0.1497	0.1497

Table 5. Weights of the criteria matrix $\left(w{=}[w_f]_q\right)$

Criteria	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8	A_9	A_{10}
Weights (w_f)	0.1104	0.1309	0.0720	0.1023	0.1131	0.1077	0.0560	0.1282	0.0875	0.0920

Table 6. Final weighted matrix $\left(N = [N_e]_p\right)$ for alternative ranking

Alternatives	T_1	T_2	T_3	T_4	T_5
Scores (N_e)	0.8663	1.0215	1.0485	0.6791	0.9510
Ranks	4th	2nd	1st	5th	3rd

"OSCAR TOS (T_4)." Consequently, T_3 was identified as the best TOS for green ports, followed by T_2. Thus, in terms of TOS performance in green ports in Türkiye, Navis TOS stands out as the most successful TOS.

4.1. Sensitivity analyses

In this study, SASs were employed to assess the robustness of the IF–LODECI–ALWAS hybrid model and to validate the results. The fundamental objective of these scenarios was to test whether the results obtained aligned with the research findings when conditions and parameters were altered. Five SASs focusing on the selection of TOS for green ports were formulated. These SASs are as follows:

(i) SAS-1: If the expert weights in the algorithm of the IF–LODECI–ALWAS model are assumed to be equal, how does the TOS ranking change when rerunning the algorithm?
(ii) SAS-2: When each criterion is excluded from the decision model and the algorithm is rerun, how does the TOS ranking change?
(iii) SAS-3: When each alternative is excluded from the decision model and the algorithm is rerun, how does the TOS ranking change?
(iv) SAS-4: If values of 2, 3, 4, and 5 are assigned to the parameter θ, how does the TOS alternative ranking change?
(v) SAS-5: If values between 0.1 and 0.9 are assigned to the parameter μ, how does the TOS alternative ranking change?

The outcomes of the sensitivity analysis are as follows:

(i) According to the findings of SAS-1 (**Table 7**), maintaining the constant values of expert importance levels did not yield any observable changes in the TOS rankings. This observation leads to the conclusion that expert weights do not exert a significant impact during the decision model process.

(ii) Within the scope of SAS-2 (**Table 7**), 10 subscenarios were generated. In each subscenario, starting with the first criterion, each criterion was sequentially excluded from the decision model, and the algorithm was rerun. In all scenarios except those where the first (SAS-2a) and fourth criteria (SAS-2d) were excluded, the best TOS was consistently identified as "Navis TOS (T_3)." However, in scenarios SAS-2a and SAS-2d, the optimal criterion was identified as "GullsEye TOS (T_2)."

(iii) Within the framework of SAS-3 (**Table 7**), five subscenarios were established. In each subscenario, one TOS was excluded from the decision model. Then, the algorithm was reapplied. All subscenarios of SAS-3 align consistently with the research findings.

(iv) Within the scope of SAS-4 (**Figure 3**), the values assigned to the parameter θ were compared with the original research results obtained when θ was set to 1. Across all values assigned to the parameter θ, no variation was observed in the TOS rankings in the algorithm results.

(v) Under the purview of SAS-5, various values were assigned to the parameter μ. The primary rationale behind these assignments was to observe the impact of fluctuations in weights between the Aczel–Alsina weighted arithmetic mean strategy and the Aczel–Alsina weighted geometric mean strategy on the TOS rankings. According to the results of SAS-5 (**Figure 4**), when the weight of the Aczel–Alsina weighted arithmetic mean strategy was at its lowest level, "GullsEye TOS (T_2)" was identified as the optimal alternative, while "Navis TOS (T_3)" was determined as the best alternative in all other options. This observation distinctly highlights the combined influence of both strategies on the decision model.

Ultimately, the findings of all SASs indicate the robustness of the IF–LODECI–ALWAS hybrid model and align with the research results. Therefore, it is affirmed that the algorithm developed for TOS selection is robust. The primary advantage of the IF–LODECI–ALWAS model lies in its ability to effectively manage uncertainty and hesitation in expert judgments using IF sets, while integrating nonlinear Aczel–Alsina operations to enhance computational flexibility and precision. This combination provides a more realistic and adaptive framework for complex decision-making environments, such as TOS selection in green ports. However, the model's main limitation is its relatively high computational complexity, which may increase the time cost for large-scale applications.

4.2. Comparative analyses

To support the consistency and robustness of the results obtained through the IF–LODECI–ALWAS hybrid model, comparative analyses were conducted using several MCDM methods. In this context, the case study was reapplied employing the measurement of alternatives and ranking according to compromise solution (MARCOS), root assessment method (RAM), simple additive weighting (SAW), weighted aggregated sum product assessment (WASPAS), alternative ranking order method accounting for two-step normalization (AROMAN), and multiattributive border approximation area comparison (MABAC) methods. During this stage, the criterion weights derived from the LODECI method were used as the weighting parameters for all comparative methods.

The comparison results revealed that, similar to the ALWAS method, SolonPort TOS was identified as the best-performing alternative in the MARCOS, RAM, SAW, and WASPAS methods. In contrast, the GullsEye TOS was determined to be the best option in the AROMAN and MABAC methods. In contrast, the OSCAR TOS consistently ranked as the lowest-performing alternative across all methods. **Figure 5** presents the comparative results obtained from the ALWAS method alongside other MCDM techniques.

When examining the correlations among the ranking results, the strongest correlation was observed between the ALWAS and WASPAS methods (0.9989). Moreover, the correlations between the ALWAS method and the SAW, RAM, or MARCOS methods were all greater than 0.9000. The correlations between ALWAS and the AROMAN or MABAC methods ranged from 0.8500 to 0.9000. These findings demonstrate that the results obtained from different alternative ranking methods are consistent with those of the IF–LODECI–ALWAS hybrid model, thereby confirming the robustness and reliability of the proposed approach.

4.3. Research implications

In this study, a hybrid model for selecting TOS in green ports was developed. The hybrid model and the research yield numerous implications, outlined as follows:

Table 7. Results of SAS-1, SAS-2, and SAS-3.

SAS	Scenarios	TOS ranking	Best TOS
SAS-1	Expert significance levels are equal	$T_3 > T_2 > T_5 > T_1 > T_4$	Navis TOS
SAS-2a	1st criterion is excluded	$T_2 > T_3 > T_1 > T_5 > T_4$	GullsEye TOS
SAS-2b	2nd criterion is excluded	$T_3 > T_2 > T_5 > T_1 > T_4$	Navis TOS
SAS-2c	3rd criterion is excluded	$T_3 > T_2 > T_5 > T_1 > T_4$	Navis TOS
SAS-2d	4th criterion is excluded	$T_2 > T_3 > T_5 > T_1 > T_4$	GullsEye TOS
SAS-2e	5th criterion is excluded	$T_3 > T_2 > T_5 > T_1 > T_4$	Navis TOS
SAS-2f	6th criterion is excluded	$T_3 > T_2 > T_5 > T_1 > T_4$	Navis TOS
SAS-2g	7th criterion is excluded	$T_3 > T_2 > T_5 > T_1 > T_4$	Navis TOS
SAS-2h	8th criterion is excluded	$T_3 > T_2 > T_5 > T_1 > T_4$	Navis TOS
SAS-2ı	9th criterion is excluded	$T_3 > T_2 > T_5 > T_1 > T_4$	Navis TOS
SAS-2j	10th criterion is excluded	$T_3 > T_5 > T_2 > T_1 > T_4$	Navis TOS
SAS-3a	1st alternative is excluded	$T_3 > T_2 > T_5 > T_4$	Navis TOS
SAS-3b	2nd alternative is excluded	$T_3 > T_5 > T_1 > T_4$	Navis TOS
SAS-3c	3rd alternative is excluded	$T_2 > T_5 > T_1 > T_4$	GullsEye TOS
SAS-3d	4th alternative is excluded	$T_3 > T_2 > T_5 > T_1$	Navis TOS
SAS-3e	5th alternative is excluded	$T_3 > T_2 > T_1 > T_4$	Navis TOS

Abbreviations: SAS, Sensitivity analysis scenarios; TOS, Terminal operating system.

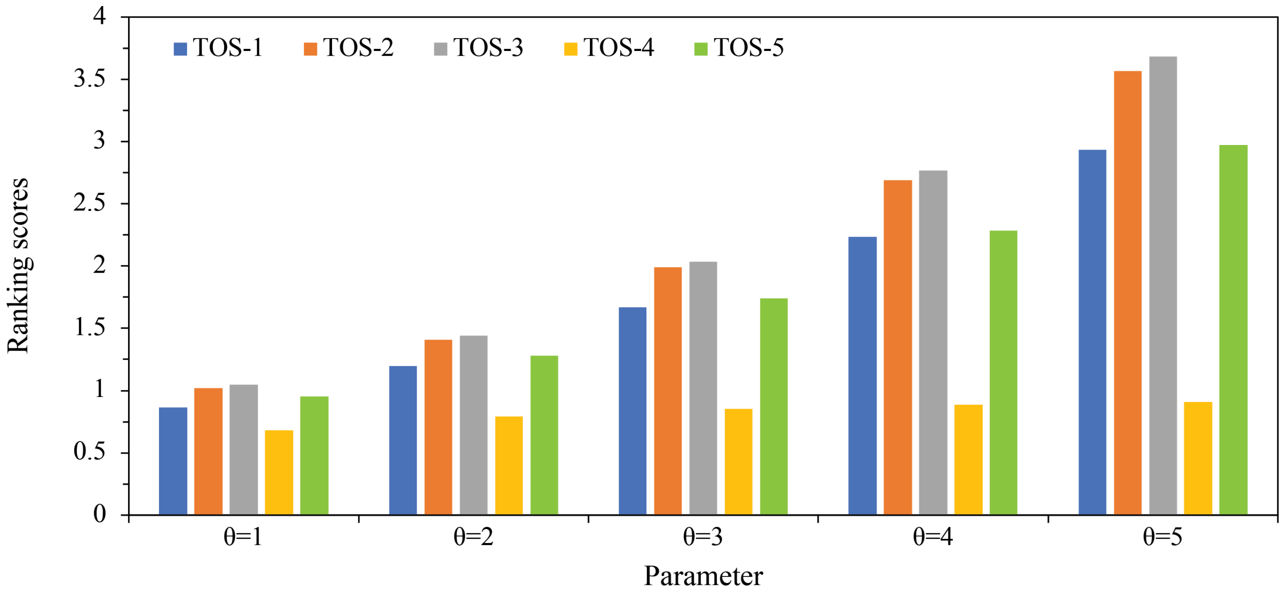

Figure 3. Results of sensitivity analysis scenario 4
Abbreviation: TOS: Terminal operating system.

(i) Decision-making framework for green ports: The developed IF–LODECI–ALWAS hybrid model presents a comprehensive decision-making framework for the selection of TOS in green ports. Researchers in the field of maritime logistics and sustainability can leverage this framework to enhance the decision-making process for environmentally conscious port management.

(ii) Integration of IF logic: The integration of IF sets in the model introduces a nuanced approach to handling uncertainties and imprecise information. This aspect contributes to the improvement in multifaceted and dynamic maritime environments.

(iii) IF–LODECI weighting methodology: The integration of the IF–LODECI model for weighting criteria in the proposed hybrid model provides a structured and systematic approach. Researchers interested in MCDM can explore and apply the IF–LODECI model in diverse contexts to improve the accuracy of weighting procedures.

(iv) Application of Aczel–Alsina operations: The utilization of Aczel–Alsina t-norm and t-conorm operations, along with the IFAAWA aggregation operator, enhances the robustness of the proposed

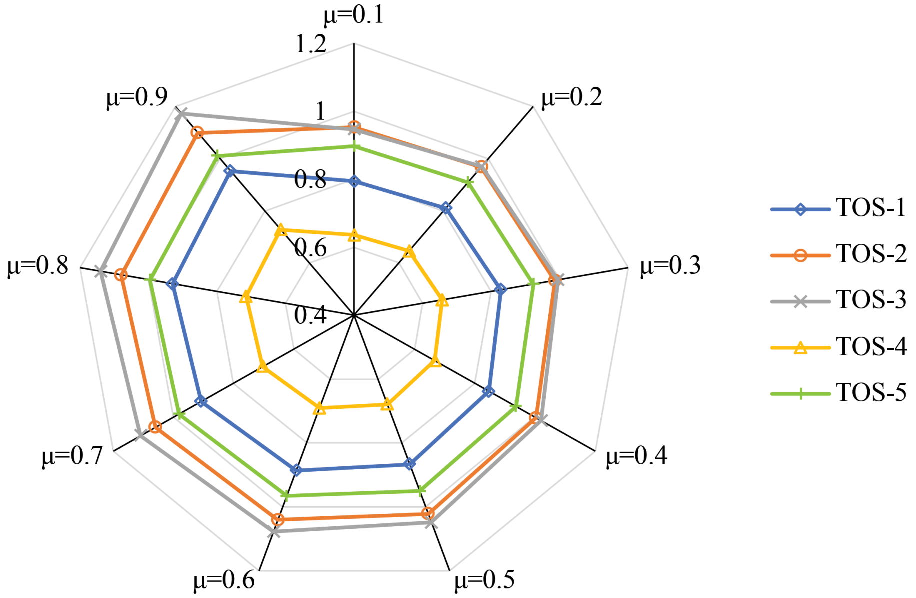

Figure 4. Results of sensitivity analysis scenario 5
Abbreviation: TOS: Terminal operating system.

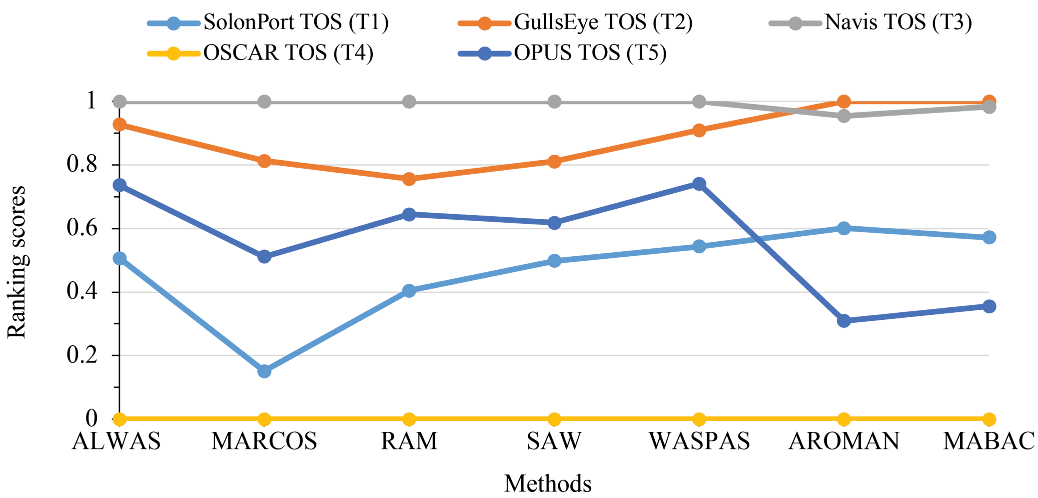

Figure 5. Comparative analysis results of TOSs across multicriteria decision-making methods
Abbreviations: ALWAS: Aczel–Alsina weighted assessment; AROMAN: Alternative ranking order method accounting for two-step normalization; MABAC: Multiattributive border approximation area comparison; MARCOS: Measurement of alternatives and ranking according to compromise solution; RAM: Root assessment method; SAW: Simple additive weighting; TOS, Terminal operating system; WASPAS: Weighted aggregated sum product assessment.

hybrid model. This application contributes to the growing body of knowledge in the field of fuzzy logic and aggregation techniques for decision support systems.

(v) Real-world case study: The case study of the green ports in Türkiye demonstrates the practical applicability of the developed hybrid model. Researchers and port authorities can draw insights from this case study when implementing similar decision-making processes in other green port initiatives.

(vi) Sensitivity analysis: The incorporation of SASs to test the model's robustness provides valuable insights into the reliability and stability of the proposed approach. Future research can explore additional sensitivity analyses to further validate and refine the model under various conditions.

This research not only contributes to the field of green port management but also provides a foundation for future studies to build upon and refine decision-making processes in the context of environmentally conscious port operations.

4.4. Managerial implications

By addressing the improvement of green port performance through a dedicated focus on the selection of TOS, this research proposed a model that offers a green-centric approach. The development of this model has numerous managerial implications aimed at enhancing its utilization in administrative activities. These managerial implications are outlined as follows:

(i) Enhanced decision support for green ports: The developed hybrid model provides a robust decision-making framework for the selection of TOS in green ports. Port managers can leverage this model to enhance decision support, leading to more informed and sustainable choices in TOS selection.

(ii) Strategic embrace of green TOS: The emphasis on the importance of green TOS highlights a strategic approach toward environmental sustainability in port operations. Port authorities are encouraged to prioritize and integrate eco-friendly TOS to align with global green initiatives and regulations.

(iii) Robust stability with maximum decomposition approach: The adoption of the maximum decomposition approach in the IF–LODECI–ALWAS hybrid model enhances the stability of weighting factors. Port decision-makers can rely on this feature to ensure the resilience of the decision model under varying conditions and uncertainties.

(iv) Effective alternative evaluation with IF-ALWAS methodology: The application of the IF–ALWAS methodology for alternative evaluation, based on Aczel–Alsina nonlinear functions, supports an effective and nuanced assessment of TOS alternatives. Port managers can benefit from a comprehensive evaluation process that considers fuzzy logic in decision-making.

(v) Practical applicability: The implementation of the proposed framework at the green ports in Türkiye, as demonstrated in the case study, provides tangible evidence of the model's practical relevance and effectiveness within the context of a real-world green port environment. Port managers can draw insights from the case study to enhance the environmental performance of their ports.

(vi) Guidance for green port management: The research outcomes offer valuable insights and guidance for green port managers, emphasizing the importance of environmental considerations in TOS selection. Managers are encouraged to adopt a holistic approach that aligns sustainability goals and enhances the overall environmental performance of their ports.

The outlined managerial implications contribute to the strategic and operational aspects of green port management, providing actionable insights for port authorities aiming to enhance their environmental performance through informed TOS selection.

4.5. Limitations

The study acknowledges certain limitations and constraints, which are outlined below:

(i) Data scope: While the research focused on the selection of TOS in green ports, the potential generalization of the results might be limited by the relatively narrow scope of the data. A more extensive data set could enhance the generalizability of the findings.

(ii) Applicability: Testing the model in different industrial contexts could provide a more comprehensive understanding of its general acceptance and usability.

(iii) Expert group selection: The selection of the expert group used in the study was confined to a specific geographic region and industry. Conducting studies with diverse expert groups could better evaluate the model's overall acceptability and usability.

(iv) Computational complexity and scalability: While the proposed IF–LODECI–ALWAS hybrid algorithm demonstrates robust performance, its computational complexity (including time cost and potential convergence issues) requires further investigation, particularly for large-scale applications.

4.6. Future directions

While this study made significant contributions to understanding the selection of TOS in green ports, the following avenues for future research could enrich and expand upon the current findings:

(i) Develop dynamic decision-making models that can adapt to changing environmental conditions, market trends, and technological advancements. This would contribute to the resilience of TOS selection strategies in the face of uncertainties.

(ii) Conduct cross-regional and cross-cultural studies to compare TOS selection criteria and models across different green ports worldwide. This could lead to the identification of region-specific factors influencing TOS preferences.

(iii) Investigate effective strategies for engaging a broader range of stakeholders, including local communities, environmental groups, and government agencies, in the TOS selection process. Understanding diverse perspectives can lead to more inclusive and sustainable decision-making.

(iv) Conduct a comprehensive cost-benefit analysis of implementing green TOS, considering not only the initial investment but also the long-term economic, environmental, and social benefits. This would help decision-makers understand the holistic value proposition.
(v) Explore the role of human factors, including decision-makers' perceptions, attitudes, and cognitive biases, in the TOS selection process. This could lead to the development of decision support systems that take into account human decision-making dynamics.
(vi) Foster collaborative research initiatives involving academia, industry stakeholders, and governmental bodies. Such partnerships can facilitate the exchange of knowledge, data, and best practices, contributing to a more comprehensive understanding of green port management.
(vii) Automate the model through implementation in programming languages, such as Python or MATLAB, or integration with existing port management software to provide more specificity and enhance its practical applicability.

5. Conclusion

This research focused on the selection of TOS within the context of green ports, aiming to identify and define the key criteria that influence the provision of port services. An MCDM approach, based on expert group evaluations and IF sets, was adopted to handle uncertainty and subjectivity in expert judgments. The primary objective of the study was to develop a decision-support algorithm for selecting TOS that enhances the overall operational and environmental performance of green ports.

The study introduced a hybrid IF–LODECI–ALWAS model, integrating the IF–LODECI method for criterion weighting and the IF–ALWAS method for alternative evaluation. The IF–LODECI method, which incorporates the maximum decomposition approach, provides robust stabilization of weights. Meanwhile, the IF–ALWAS method, derived from Aczel–Alsina nonlinear functions, ensures a precise and flexible evaluation process. Furthermore, the hybrid model utilizes Aczel–Alsina t-norm and t-conorm operations, along with the IFAAWA aggregation operator, to improve computational accuracy and decision reliability.

The hybrid model was applied through a real-world case study conducted at green ports in Türkiye. The case involved six experts, 10 evaluation criteria, and five TOS alternatives, providing a comprehensive framework for sustainable port management. The results revealed that berth management and scheduling (0.1309) emerged as the most influential criterion, highlighting the importance of operational efficiency in green port operations. Among the evaluated alternatives, Navis TOS (1.0485) demonstrated the highest overall performance, aligning well with sustainability and performance-oriented goals.

To verify the robustness of the proposed hybrid model, extensive sensitivity analyses were conducted under multiple scenarios. These analyses consistently confirmed the model's stability and the reliability of its outcomes, validating its capability to support complex decision-making processes. The findings also demonstrated that integrating IF logic with Aczel–Alsina-based MCDM methods can effectively manage uncertainties in expert-based evaluations, providing practical guidance for port managers.

In conclusion, this study bridges the gap between theoretical decision-making models and their practical implementation in the maritime industry. The IF–LODECI–ALWAS framework provides both academic and managerial contributions by offering a holistic, transparent, and replicable model for TOS selection in green ports. Future research is recommended to conduct comparative analyses with other MCDM methods, automate the proposed model using programming environments, such as Python and MATLAB, and integrate it with port management software to further enhance decision support capabilities in sustainable port operations.

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Conflict of interest

The authors declare they have no competing interests.

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Conceptualization: Pinar Gürol
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Writing–original draft: All authors
Writing–review & editing: All authors

Availability of data

Data are available from the authors upon reasonable request.

AI tools statement

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

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Appendix

A1. Preliminaries of intuitionistic fuzzy sets

This section provides the preliminaries of intuitionistic fuzzy (IF) sets.
(i) Definition A1:

In the specified discourse domain, denoted as Z, the notation $\widetilde{Y}$, defined by the formulation in **Equation (A1)**, indicates the presence of a collection of IF sets functioning within the broader context of set Z[27]

$$\widetilde{Y}=\left\{\left\langle z,\ \beta_{\widetilde{Y}}(z),?_{\widetilde{Y}}(z)\ \mid z\in Z\right\rangle\right\} \tag{A1}$$

The functions $\left\{\beta_{\widetilde{Y}}(z):\widetilde{Y}?[0,1],\ ?_{\widetilde{Y}}(z):\widetilde{Y}?[0,1]\right\}$ can be construed as representing the degrees of membership and nonmembership, respectively. These functions are precisely characterized while adhering to the constraint that the inequality $0=\beta_{\widetilde{Y}}(z)+?_{\widetilde{Y}}(z)=1$ holds for all elements z within the set Z. The indeterminacy degree of z, denoted as $p_{\widetilde{Y}}(z)$, and its computation is expressed as in **Equation (A2)**:

$$p_{\widetilde{Y}}(z)=1-\beta_{\widetilde{Y}}(z)-?_{\widetilde{Y}}(z),\ \forall\ z\in Z \tag{A2}$$

(ii) Definition A2:

Within the context of IF sets, a sequence of operative methodologies is employed. These methodologies, delineated by Atanassov,[38] are articulated as follows: Consider the presence of two IF set entities, specifically denoted as $\widetilde{Y}_1$ and $\widetilde{Y}_2$, established over the universal set Z, with their respective components expressed as follows: $\widetilde{Y}_1=\left(\beta_{\widetilde{Y}_1}(z),?_{\widetilde{Y}_1}(z)\right)$, $\widetilde{Y}_2=\left(\beta_{\widetilde{Y}_2}(z),?_{\widetilde{Y}_2}(z)\right)$. The explication of the principles dictating the interrelations among these two entities of IF sets is delineated as follows (for $\omega>0$):

i $\widetilde{Y}_1\subseteq\widetilde{Y}_2$, if $\beta_{\widetilde{Y}_1}(z)=\beta_{\widetilde{Y}_2}(z)$ and $?_{\widetilde{Y}_2}(z)=?_{\widetilde{Y}_1}(z)$, $\forall\ z\in Z$,
ii $\widetilde{Y}_1=\widetilde{Y}_2$, if $\widetilde{Y}_1\subseteq\widetilde{Y}_2$ and $\widetilde{Y}_2\subseteq\widetilde{Y}_1$,
iii $\widetilde{Y}_1\cup\widetilde{Y}_2=\left\{\left\langle z,max\left(\beta_{\widetilde{Y}_1}(z),\beta_{\widetilde{Y}_2}(z)\right),\ min\left(?_{\widetilde{Y}_1}(z),?_{\widetilde{Y}_2}(z)\right)\mid z\in Z\right\rangle\right\}$,
iv $\widetilde{Y}_1 n\widetilde{Y}_2=\left\{\left\langle z,min\left(\beta_{\widetilde{Y}_1}(z),\beta_{\widetilde{Y}_2}(z)\right),\ max\left(?_{\widetilde{Y}_1}(z),?_{\widetilde{Y}_2}(z)\right)\mid z\in Z\right\rangle\right\}$,
v $\widetilde{Y}_1\oplus\widetilde{Y}_2=\left\{\left\langle z,\left(\beta_{\widetilde{Y}_1}(z)+\beta_{\widetilde{Y}_2}(z)-\left(\beta_{\widetilde{Y}_1}(z)\beta_{\widetilde{Y}_2}(z)\right)\right),\left(?_{\widetilde{Y}_1}(z)?_{\widetilde{Y}_2}(z)\right)\ \mid z\in Z\right\rangle\right\}$,
vi $\widetilde{Y}_1\bigotimes\widetilde{Y}_2=\left\{\left\langle z,\left(\beta_{\widetilde{Y}_1}(z)\beta_{\widetilde{Y}_2}(z)\right),\left(?_{\widetilde{Y}_1}(z)+?_{\widetilde{Y}_2}(z)-\left(?_{\widetilde{Y}_1}(z)?_{\widetilde{Y}_2}(z)\right)\right)\ \mid z\in Z\right\rangle\right\}$,
vii $\omega\widetilde{Y}_1=\left\{\left\langle z,\left(1-\left(1-\beta_{\widetilde{Y}_1}(z)\right)^{\omega}\right),\left(?_{\widetilde{Y}_1}(z)\right)^{\omega}\mid z\in Z\right\rangle\right\}$,
viii $\left(\widetilde{Y}_1\right)^{\omega}=\left\{\left\langle z,\left(\beta_{\widetilde{Y}_1}(z)\right)^{\omega},\left(1-\left(1-?_{\widetilde{Y}_1}(z)\right)^{\omega}\right)\ \mid z\in Z\right\rangle\right\}$.

In accordance with the established principles, it is expected that Definition A2 will align with the following criteria:

i $\widetilde{Y}_1\oplus\widetilde{Y}_2=\widetilde{Y}_2\oplus\widetilde{Y}_1$,
ii $\widetilde{Y}_1\bigotimes\widetilde{Y}_2=\widetilde{Y}_2\bigotimes\widetilde{Y}_1$,
iii $\omega\left(\widetilde{Y}_1\oplus\widetilde{Y}_2\right)=\omega\widetilde{Y}_1\oplus\omega\widetilde{Y}_2\ for\ \omega>0$,
iv $\left(\widetilde{Y}_1\bigotimes\widetilde{Y}_2\right)^{\omega}=\widetilde{Y}_1^{\omega}\bigotimes\widetilde{Y}_2^{\omega}\ for\ \omega>0$,
v $\omega_1\widetilde{Y}_1\oplus\omega_2\widetilde{Y}_1=(\omega_1+\omega_2)\widetilde{Y}_1 for\ \omega_1,\omega_2>0$,
vi $\widetilde{Y}_1^{\omega_1}\int\widetilde{Y}_1^{\omega_2}=\widetilde{Y}_1^{(\omega_1+\omega_2)}\ for\ \omega_1,\omega_2>0$.

(iii) Definition A3:

Contemplate the existence of an IF-set entity, precisely designated as $\widetilde{Y}$, established over the universal set Z, with its respective components articulated as follows: $\widetilde{Y}=\left(\beta_{\widetilde{Y}}(z),?_{\widetilde{Y}}(z)\right)$. The computation of the score function, represented as $S\left(\widetilde{Y}\right)$, is executed utilizing **Equation (A3)**, while the determination of the accuracy function, denoted as $A\left(\widetilde{Y}\right)$, is ascertained through the application of **Equation (A4)**:

$$S\left(\widetilde{Y}\right)=\beta_{\widetilde{Y}}(z)-?_{\widetilde{Y}}(z) \tag{A3}$$

$$A\left(\widetilde{Y}\right)=\beta_{\widetilde{Y}}\left(z\right)+?_{\widetilde{Y}}\left(z\right) \tag{A4}$$

(iv) Definition A4:

Consider the presence of two IF set entities, specifically denoted as $\widetilde{Y}_1$ and $\widetilde{Y}_2$, established over the universal set Z, with their respective components expressed as follows: $\widetilde{Y}_1=\left(\beta_{\widetilde{Y}_1}\left(z\right),?_{\widetilde{Y}_1}\left(z\right)\right)$, $\widetilde{Y}_2=\left(\beta_{\widetilde{Y}_2}\left(z\right),?_{\widetilde{Y}_2}\left(z\right)\right)$. In the context where $S\left(\widetilde{Y}_i\right)$ and $A\left(\widetilde{Y}_i\right)$ denote the score and accuracy functions of $\widetilde{Y}_i$ $(i=1,2)$, the establishment of ordinal relations can be achieved in the following manner:

i If $S\left(\widetilde{Y}_1\right)>S\left(\widetilde{Y}_2\right)$, then $\widetilde{Y}_1$ greater than $\widetilde{Y}_2$,

ii If $S\left(\widetilde{Y}_1\right)=S\left(\widetilde{Y}_2\right)$ and $A\left(\widetilde{Y}_1\right)>A\left(\widetilde{Y}_2\right)$, then $\widetilde{Y}_1$ greater than $\widetilde{Y}_2$,

iii If $S\left(\widetilde{Y}_1\right)=S\left(\widetilde{Y}_2\right)$, $A\left(\widetilde{Y}_1\right)=A\left(\widetilde{Y}_2\right)$, then $\widetilde{Y}_1$ is equal to $\widetilde{Y}_2$.

A2. Aczel-Alsina operations in intuitionistic fuzzy sets

This section offers an elucidation of Aczel–Alsina operations and outlines their applications to IF sets.

(i) Definition A5:

The Aczel–Alsina t-norm $\left(\Gamma^{\theta}\left(a,b\right)\right)$ and t-conorm $\left(\Gamma^{*\theta}\left(a,b\right)\right)$, expressed in **Equation (A5)** and **Equation (A6)**, respectively, are introduced by Aczel and Alsina[39]:

$$\Gamma^{\theta}\left(a,b\right)=\begin{cases}\Gamma_D\left(a,b\right), & if\ \theta=0\\ min\left(a,b\right), & if\ \theta=8\\ e^{-\left(\left(-log(a)\ \right)^{\theta}+\left(-log(b)\ \right)^{\theta}\right)^{1/\theta}}, & otherwise\end{cases}, \tag{A5}$$

$$\Gamma^{*\theta}\left(a,b\right)=\begin{cases}\Gamma_D^{*}\left(a,b\right), & if\ \theta=0\\ max\left(a,b\right), & if\ \theta=8\\ 1-e^{-\left(\left(-log(1-a)\ \right)^{\theta}+\left(-log(1-b)\ \right)^{\theta}\right)^{1/\theta}}, & otherwise\end{cases}, \tag{A6}$$

where $\theta\in[0,8]$; $a,b\in[0,1]$.

Consider the presence of two IF set entities, specifically denoted as $\widetilde{Y}_1$ and $\widetilde{Y}_2$, established over the universal set Z, with their respective components expressed as follows: $\widetilde{Y}_1=\left(\beta_{\widetilde{Y}_1}\left(z\right),?_{\widetilde{Y}_1}\left(z\right)\right)$, $\widetilde{Y}_2=\left(\beta_{\widetilde{Y}_2}\left(z\right),?_{\widetilde{Y}_2}\left(z\right)\right)$. The Aczel–Alsina product $\left(\widetilde{Y}_1\cap_{\Gamma^{\beta},\Gamma^{*\beta}}\widetilde{Y}_2\right)$ and Aczel–Alsina sum $\left(\widetilde{Y}_1\cup_{\Gamma^{\theta},\Gamma^{*\theta}}\widetilde{Y}_2\right)$ incorporating the t-norm $\left(\Gamma^{\theta}\right)$ and t-conorm $\left(\Gamma^{*\theta}\right)$ are expressed through **Equation (A7)** and **Equation (A8)**, respectively:

$$\widetilde{Y}_1\cap_{\Gamma^{\theta},\Gamma^{*\theta}}\widetilde{Y}_2=\left(\Gamma^{\theta}\left(\beta_{\widetilde{Y}_1}\left(z\right),\beta_{\widetilde{Y}_2}\left(z\right)\right),\Gamma^{*\theta}\left(\gamma_{\widetilde{Y}_1}\left(z\right),\gamma_{\widetilde{Y}_2}\left(z\right)\right)\right) \tag{A7}$$

$$\widetilde{Y}_1\cup_{\Gamma^{*\theta},\Gamma^{\theta}}\widetilde{Y}_2=\left(\Gamma^{*\theta}\left(\beta_{\widetilde{Y}_1}\left(z\right),\beta_{\widetilde{Y}_2}\left(z\right)\right),\Gamma^{\theta}\left(\gamma_{\widetilde{Y}_1}\left(z\right),\gamma_{\widetilde{Y}_2}\left(z\right)\right)\right) \tag{A8}$$

(ii) Definition A6:

Consider the presence of two IF set entities, specifically denoted as $\widetilde{Y}_1$ and $\widetilde{Y}_2$, established over the universal set Z, with their respective components expressed as follows: $\widetilde{Y}_1=\left(\beta_{\widetilde{Y}_1}\left(z\right),\gamma_{\widetilde{Y}_1}\left(z\right)\right)$, $\widetilde{Y}_2=\left(\beta_{\widetilde{Y}_2}\left(z\right),\gamma_{\widetilde{Y}_2}\left(z\right)\right)$. The procedures dictating the interaction between two IF sets, utilizing the Aczel–Alsina t-norm and Aczel–Alsina t-conorm, are elucidated as follows, under the condition that $\theta>0$ and $\omega>0$[35]:

i

$$\widetilde{Y}_1\oplus\widetilde{Y}_2=\left\{\left\langle z,\left(1-e^{-\left(\left(-log\left(1-\beta_{\widetilde{Y}_1}(z)\right)\ \right)^{\theta}+\left(-log\left(1-\beta_{\widetilde{Y}_2}(z)\right)\ \right)^{\theta}\right)^{1/\theta}}\right),\right.\right.$$

$$\left(e^{-\left(\left(-log\left(?y_{\widetilde{Y}_1}(z)\right)\ \right)^{\theta}+\left(-log\left(\gamma_{\widetilde{Y}_2}(z)\right)\ \right)^{\theta}\right)^{1/\theta}}\right)\ |\ z\in Z,$$

ii

$$\widetilde{Y}_1 \bigotimes \widetilde{Y}_2 = \left\{ \left\langle z, \left(e^{-\left(\left(-log\left(\beta_{\widetilde{Y}_1}(z) \right) \right)^{\theta} + \left(-log\left(\beta_{\widetilde{Y}_2}(z) \right) \right)^{\theta} \right)^{1/\theta}} \right), \left(1 - e^{-\left(\left(-log\left(1 - ?y_{\widetilde{Y}_1}(z) \right) \right)^{\theta} + \left(-log\left(1 - ?y_{\widetilde{Y}_2}(z) \right) \right)^{\theta} \right)^{1/\theta}} \right) \mid z \in Z, \right.\right.$$

iii

$$\omega \widetilde{Y}_1 = \left\{ \left\langle z, \left(1 - e^{-\left(\omega \left(-log\left(1 - \beta_{\widetilde{Y}_1}(z) \right) \right)^{\theta} \right)^{1/\theta}} \right), \left(e^{-\left(\omega \left(-log\left(\gamma_{\widetilde{Y}_1}(z) \right) \right)^{\theta} \right)^{1/\theta}} \right) \mid z \in Z, \right.\right.$$

iv

$$\left(\widetilde{Y}_1 \right)^{\omega} = \left\{ \left\langle z, \left(e^{-\left(\omega \left(-log\left(\beta_{\widetilde{Y}_1}(z) \right) \right)^{\theta} \right)^{1/\theta}} \right), \left(1 - e^{-\left(\omega \left(-log\left(1 - ?y_{\widetilde{Y}_1}(z) \right) \right)^{\theta} \right)^{1/\theta}} \right) \mid z \in Z. \right.\right.$$

- Theorem A1: Consider the presence of two IF set entities, specifically denoted as $\widetilde{Y}_1$ and $\widetilde{Y}_2$, established over the universal set Z, with their respective components expressed as follows: $\widetilde{Y}_1 = \left(\beta_{\widetilde{Y}_1}(z), \gamma_{\widetilde{Y}_1}(z) \right)$, $\widetilde{Y}_2 = \left(\beta_{\widetilde{Y}_2}(z), \gamma_{\widetilde{Y}_2}(z) \right)$. Utilizing Aczel–Alsina t-norm $\left(\Gamma^{\theta} \right)$ and t-conorm $\left(\Gamma^{*\theta} \right)$, these procedures involve the cooperative interaction between two IF sets as detailed in the following manner[35]:

i $\widetilde{Y}_1 \oplus \widetilde{Y}_2 = \widetilde{Y}_2 \oplus \widetilde{Y}_1,$

ii $\widetilde{Y}_1 \bigotimes \widetilde{Y}_2 = \widetilde{Y}_2 \bigotimes \widetilde{Y}_1,$

iii $\omega \left(\widetilde{Y}_1 \oplus \widetilde{Y}_2 \right) = \omega \widetilde{Y}_1 \oplus \omega \widetilde{Y}_2 \ for\ \omega > 0,$

iv $\left(\widetilde{Y}_1 \bigotimes \widetilde{Y}_2 \right)^{\omega} = \widetilde{Y}_1^{\omega} \bigotimes \widetilde{Y}_2^{\omega} \ for\ \omega > 0,$

v $\omega_1 \widetilde{Y}_1 \oplus \omega_2 \widetilde{Y}_1 = (\omega_1 + \omega_2) \widetilde{Y}_1 for\ \omega_1, \omega_2 > 0,$

vi $\widetilde{Y}_1^{\omega_1} \int \widetilde{Y}_1^{\omega_2} = \widetilde{Y}_1^{(\omega_1 + \omega_2)} \ for\ \omega_1, \omega_2 > 0.$

- Proof: The validation of Theorem A1 has been substantiated in the investigation conducted by Senapati et al.[35]

A3. Intuitionistic fuzzy–Aczel–Alsina weighted averaging aggregation operators

This section elucidates the IF–Aczel–Alsina weighted averaging (IFAAWA) aggregation operators.

(i) Definition A7: Assume the set $\widetilde{Y}_\xi$ ($\xi = 1, 2, \ldots, \kappa$), represented as $\widetilde{Y}_\xi = \left(\beta_{\widetilde{Y}_\xi}(z), ?y_{\widetilde{Y}_\xi}(z) \right)$, constitutes an IF set. The corresponding weight vector is identified as $\omega_\xi = (\omega_1, \omega_2, \ldots, \omega_\kappa)$, where $\omega_\xi \ \varepsilon\ [0,1]$, $\sum_{\xi=1}^{\kappa} \omega_\xi = 1$, and $\theta > 0$. In this framework, the IFAAWA aggregation operator is formulated as **Equation (A9)**:

$$IFAAWA \left(\widetilde{Y}_1, \widetilde{Y}_2, \ldots, \widetilde{Y}_\kappa \right) = \oplus_{\xi=1}^{\kappa} \omega_\xi \widetilde{Y}_\xi \tag{A9}$$

- Theorem A2: For Definition A7, the IFAAWA aggregation operator is formulated as:

$$IFAAWA\left(\widetilde{Y}_1,\widetilde{Y}_2,\ldots,\widetilde{Y}_\kappa\right)=\oplus_{\xi=1}^{\kappa}\omega_\xi\widetilde{Y}_\xi=\left(\left(1-e^{-\left(\sum_{\xi=1}^{\kappa}\omega_\xi\left(-log\left(1-\beta_{\widetilde{Y}_\xi}(z)\right)\right)^{\theta}\right)^{1/\theta}}\right),\left(e^{-\left(\sum_{\xi=1}^{\kappa}\omega_\xi\left(-log\left(\gamma_{\widetilde{Y}_\xi}(z)\right)\right)^{\theta}\right)^{1/\theta}}\right)\right.\tag{A10}$$

- Proof: The validation of Theorem A2 has been substantiated in the investigation conducted by Senapati et al.[35]