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Robust Measurement of Airline Sustainability Performance across Economic, Social, and Environmental Dimensions

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ABSTRACT

Sustainability is a key issue for the aviation sector and requires airlines to improve their economic, social, and environmental performance simultaneously. This paper is based on the need to monitor and evaluate the sustainability performance of airlines on an annual basis. It proposes and applies the criterion importance based on sum of squares (CRISUS) - alternative ranking using two-step logarithmic normalization (ARLON) model for assessing sustainability performance across economic, social, and environmental dimensions. This paper consists of four phases: evaluation of economic, social, and environmental performance, and determination of overall sustainability performance. The findings show that economic and environmental performance reached its highest level in 2023, while social performance peaked in 2021. The study highlighted total investment, occupational health and safety training, and greenhouse gas awareness initiatives as the most important sustainability criteria. This research offers methodological and practical contributions to the evaluation of sustainability performance and provides a practical framework to support decision-making for managers.

1. Introduction

Sustainability aims to protect natural and economic resources for the future. The seventeen sustainable development goals (SDGs) and a hundred sixty-nine sub-targets set by the United Nations

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address the economic, environmental, and social dimensions of sustainable development together [1]. Sustainability is examined in three dimensions. These are economic, social and environmental dimensions. The *economic dimension* supports sustainable economic growth for future generations by ensuring the efficient and equitable use of resources [2]. The *social dimension* supports social welfare, equality, and access to basic services. It also aims to preserve knowledge, skills, and social values for future generations [3]. The *environmental dimension* aims to protect natural resources, reduce environmental damage, and ensure that economic and social development is in harmony with the environment [4]. In this context, to achieve sustainability goals, policymakers must make decisions by simultaneously evaluating economic, social, and environmental dimensions in their decision-making processes [5].

As in other sectors, the aviation industry is also adopting strategies that support economic, social, and environmental sustainability in line with the SDGs [6]. These strategies play a critical role in sustainable development, beyond simply complying with legal requirements [7,8]. Airline companies are developing systematic performance evaluation systems to develop and implement sustainability strategies. This allows them to make progress towards the SDGs [9].

Airlines must analyze their sustainability performance to achieve SDGs targets and develop strategies accordingly. Although there are various applications for sustainability performance analysis based on different parameters, a robust model is needed for a sustainability performance analysis that encompasses all economic, social, and environmental indicators. The aim of this research is to propose a model for calculating the sustainability performance of an airline. This model should be capable of identifying the importance levels of economic, social, and environmental performance criteria and determining the sustainability performance levels of airlines over the years. In this context, the criterion importance based on sum of squares (CRISUS) - alternative ranking using two-step logarithmic normalization (ARLON) model is proposed as a model for the sustainability performance analysis of airlines. This model, based on multi-criterial decision making (MCDM), provides weighting of sustainability performance criteria and presents the annual sustainability performance levels of airline companies.

The proposed CRISUS-ARLON model allows for the systematic evaluation of the economic, social, and environmental performance of airline companies over a specific period. This provides supporting analyses for preparing sustainability reports. The CRISUS criterion weighting method [10] has a two-stage normalization structure using vector and linear normalization processes. It also allows for the determination of a robust criterion weight vector by considering the standard deviations of the criteria. While other criterion weighting methods generally use a single normalization structure and consider the correlation between criteria when calculating the criterion weight vector, CRISUS provides a robust criterion weight vector through two-step normalization. The ARLON method [11], based on logarithmic normalization processes, offers advantages in sustainability performance analysis, especially in normalizing large numbers in economic indicators. Furthermore, the ARLON method is also based on two-stage normalization, thus possessing a robust normalization structure for performance ranking. It also assists in sensitivity analysis by allowing for sustainability performance calculations based on criterion type (benefit and cost) and parameter-based combinations.

This paper contributes to the literature by proposing a model for the sustainability performance analysis of an airline company, as well as providing in-depth information about the sustainability performance criteria set. Additionally, this model, which allows for the comparative determination of sustainability performance levels over the years instead of analyzing sustainability performance over a single year, provides airline companies with data on their sustainability development levels.

The following section of this paper presents a literature review of MCDM research within the airline industry, highlighting the research gap. Section 3 explains the CRISUS–ARLON model. Section 4 presents the empirical research conducted on Turkish airlines and the findings. Section 5 discusses the results in light of the literature. Section 6 presents the inferences. Section 7 contains the conclusion.

2. Literature Review

The airline industry is an important sector that contributes to trade, tourism and economic development as well as passenger and freight transportation. Therefore, it plays an important role in the development of countries. It is also affected by many global events such as wars, economic crises and epidemics. The COVID-19 pandemic had the greatest impact on the sector, significantly reducing airline revenues, and the industry only reached pre-pandemic levels in 2023. This demonstrates the airline industry's considerable vulnerability to global crises. These crises highlight the importance of evaluating performance across different dimensions for airlines to become more resilient and sustainable [12,13]. Also, increased competition and changing industry conditions are leading airlines to adopt more effective decision-making methods. Therefore, systematic approaches that evaluate different aspects of performance together are needed [14].

Pineda *et al.* [15] evaluated airline performance using a hybrid DRSA-DEMATEL-DANP-VIKOR based MCDM model. Their findings showed that financial criteria were more decisive, and stock prices were the most significant performance indicator. Bakir *et al.* [16] analyzed airline companies in eleven emerging countries using a PIPRECIA-MAIRCA based MCDM model. The analysis revealed that Air China ranked first, and operating costs were identified as the most important evaluation criterion.

Kiracı & Bakır [17] evaluated the performance of twelve Star Alliance member airlines using the CRITIC-CODAS methodology. The results showed that financial criteria were prominent, with Singapore Airlines ranking first. Alkhatib & Migdadi [18] analyzed the sustainability performance of airlines using the DEMATEL-AHP-TOPSIS method and determined that greenhouse gas emissions were the most important criterion, while Finnair was recognized as the most successful airline.

Garg & Agrawal [19] examined the Indian airline sector using the fuzzy AHP method and identified safety and security as the most important performance criteria. Kulakli & Şahin [20] evaluated low-cost carriers (LCC) in Türkiye using the Fuzzy AHP-TOPSIS method and determined that flight scheduling and route management were the most important performance criteria.

Asker [21] analyzed the financial performance of airlines using the MEREC-COBRA method and determined that Ryanair, Southwest Airlines, and Wizz Air showed the highest performance. Asker [22] also evaluated the sustainability performance of airlines in the U.S. using the MEREC-MARCOS-COBRA methods and determined that load factor was the most important criterion, with Delta, Southwest, and American Airlines being the most successful companies.

Ertuğrul & Özdarak [23] examined performance of Turkish Airlines using the MEREC-CoCoSo methods and determined that financial criteria had the highest weight, while performance improved from 2021 onward. Seker [24] evaluated the agility capabilities of low-cost carriers using the SWARA-MABAC method and determined that strategic and financial management are the most important elements for sustainable competitiveness. A literature review of MCDM research on the airline industry is presented in Table 1.

Table 1
Literature review

Research	Methods	Application Area	Key Findings
Pineda *et al.* [15]	DRSA-DEMATEL-ANP-VIKOR	Global airlines	Financial factors were found to be more important than operational factors, with stock prices identified as the most critical performance indicator.
Bakır *et al.* [16]	PIPRECIA-AIRCA	Eleven developing country airlines	Air China has become the most successful airline, with operating costs being identified as the most important criterion.
Kiracı & Bakır [17]	CRITIC-CODAS	Twelve airlines that are members of Star Alliance	Financial indicators were found to be more important than operational indicators, with Singapore Airlines ranking first.
Alkhatib & Migdadi [18]	DEMATEL-AHP-TOPSIS	European-based airlines	Greenhouse gas emissions have been identified as the most important sustainability criterion, and Finnair has been the most successful airline.
Garg & Agrawal [19]	Fuzzy AHP	Indian aviation industry	Safety and security criteria have been identified as the most important performance determinants.
Kulaklı & Şahin [20]	Fuzzy AHP-TOPSIS	Low-cost airlines in Türkiye	Flight planning and route management are the most important criteria in terms of operational efficiency.
Asker [21]	MEREC-COBRA	Thirt-two traditional and fourteen low-cost airlines	Ryanair, Southwest, and Wizz Air have demonstrated more resilient performance during the pandemic.
Asker [22]	MEREC-MARCOS-COBRA	Eleven airlines in the US	Occupancy rate has become the most important criterion both before and after the pandemic, with Delta, Southwest, and American Airlines identified as the most successful companies.
Ertuğrul & Özdarak [23]	MEREC-CoCoSo	Turkish Airlines (2020–2023)	Financial indicators received the highest weighting, while non-financial indicators were found to have a greater impact on long-term performance.
Seker [24]	SWARA-MABAC	Low-cost airlines	Strategic agility and financial management have been identified as key determinants of sustainable competitiveness.

3. Methodology Framework

This methodology presents a CRISUS-ARLON model for measuring the sustainability performance of airline companies. Criterion weights are calculated using the CRISUS method, while performance evaluation is performed using the ARLON method. The ARLON method determines economic, social, and environmental performance levels, and overall sustainability is calculated based on the average of these three dimensions. The CRISUS-ARLON model flowchart is shown in Figure 1.

3.1 Criterion Importance Based on Sum of Squares Method

The CRISUS method uses a two-stage normalization procedure combined with the standard deviation between criteria to calculate criterion weights [10]. The distinctive feature of this method, compared to other weighting techniques, lies in its hybrid structure: the standard deviation is determined using the values obtained from the first normalization, whereas the sum-of-squares is calculated based on the values derived from the second normalization. In this way, both normalization procedures are jointly utilized to determine the final criterion weights.

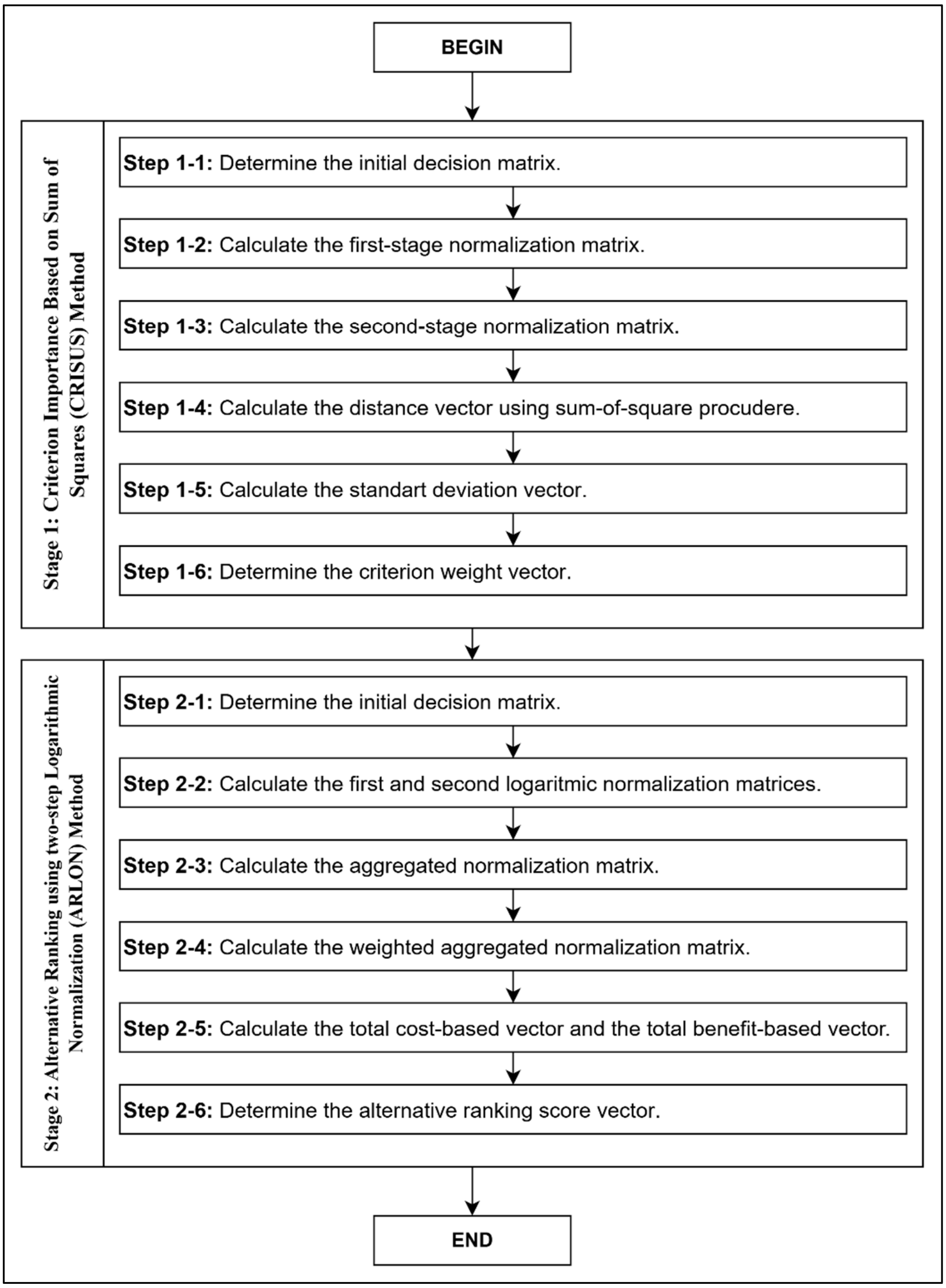

Fig. 1. The methodology (CRISUS-ARLON hybrid method)

The CRISUS method is completed in six steps, which can be outlined as follows:

Step 1*:* In the first step of the CRISUS method, the initial decision matrix $\left(X = \left[X_{ij}\right]_{MN}\right)$ is constructed. In this matrix, the values of each alternative (A_i) with respect to each criterion $\left(C_j\right)$ are presented, where X_{ij} denotes the value of the i^{th} alternative under the j^{th} criterion. Since the CRISUS method has been developed as an objective criterion weighting approach, both the criteria set $C = \left\{C_1, C_2, \dots, C_j, \dots, C_N\right\}$ $(j = 1,2, \dots, N)$ and the alternatives set $A = \{A_1, A_2, \dots, A_i, \dots, A_M\}$ $(i = 1,2, \dots, M)$ must be defined within the dataset, and the corresponding X_{ij}

values must be specified. Furthermore, within the set of criteria, two subsets should be distinguished: the cost-based criteria type and the benefit-based criteria type:

$$\boldsymbol{X}=\begin{bmatrix} X_{11} & \cdots & X_{1j} & \cdots & X_{1N} \\ \vdots & \cdots & \vdots & \cdots & \vdots \\ X_{i1} & \cdots & X_{ij} & \dots & X_{iN} \\ \vdots & \cdots & \vdots & \cdots & \vdots \\ X_{M1} & \cdots & X_{Mj} & \dots & X_{MN} \end{bmatrix}; (\boldsymbol{i}=\boldsymbol{1},\boldsymbol{2},\dots,\boldsymbol{M};\ \boldsymbol{j}=\boldsymbol{1},\boldsymbol{2},\dots,\boldsymbol{N}). \tag{1}$$

Step 2*:* In the second step, the first-stage normalization process is carried out. This normalization is based on the Euclidean distance vector normalization method (Eq. (2)). Different normalization procedures are applied according to whether the criteria are benefit-based or cost-based in this normalization process. As a result, the vector normalization matrix $\left(Z=\left[Z_{ij}\right]_{MN}\right)$ is obtained:

$$\boldsymbol{Z_{ij}}=\begin{cases} \dfrac{X_{ij}}{\sqrt{\sum_{i=1}^{M}\left(X_{ij}\right)^{2}}} \ \mathbf{for}\ \boldsymbol{j}\in\boldsymbol{C}^{+} \\ \boldsymbol{1}-\dfrac{X_{ij}}{\sqrt{\sum_{i=1}^{M}\left(X_{ij}\right)^{2}}} \ \mathbf{for}\ \boldsymbol{j}\in\boldsymbol{C}^{-} \end{cases}; (\boldsymbol{i}=\boldsymbol{1},\boldsymbol{2},\dots,\boldsymbol{M};\ \boldsymbol{j}=\boldsymbol{1},\boldsymbol{2},\dots,\boldsymbol{N}). \tag{2}$$

Step 3*:* In the third step, the second-stage normalization process is performed (Eq. (3)). At this stage, the vector-normalized values are subjected to linear normalization, regardless of whether the criteria are cost-based or benefit-based. Consequently, the data are standardized within the 0–1 range, and the linear normalization matrix $\left(G=\left[G_{ij}\right]_{MN}\right)$ is obtained:

$$\boldsymbol{G_{ij}}=\frac{Z_{ij}}{\sum_{i=1}^{M}Z_{ij}}; (\boldsymbol{i}=\boldsymbol{1},\boldsymbol{2},\dots,\boldsymbol{M};\ \boldsymbol{j}=\boldsymbol{1},\boldsymbol{2},\dots,\boldsymbol{N}). \tag{3}$$

Step 4*:* In the fourth step, the sum-of-squares procedure is applied (Eq. (4)). For each criterion, the squared values of the alternatives are summed, thereby determining the total distance associated with that criterion. In this way, a distance vector $\left(D=\left[D_{j}\right]_{N}\right)$ is obtained for each criterion:

$$\boldsymbol{D_j}=\sum_{i=1}^{M}\left(\boldsymbol{G_{ij}}\right)^{2}; (\boldsymbol{j}=\boldsymbol{1},\boldsymbol{2},\dots,\boldsymbol{N}). \tag{4}$$

Step 5*:* In the fifth step, the standard deviation calculation is performed. Using the values obtained from the first-stage (vector) normalization matrix, the standard deviation for each criterion is computed. As a result, the standard deviation vector $\left(\sigma=\left[\sigma_{j}\right]_{N}\right)$ is derived.

Step 6*:* In the sixth step, the weight coefficients for each criterion are calculated (Eq. (5)), and the criterion weight vector $\left(w=\left[w_{j}\right]_{N}\right)$ is determined. The criterion with the highest w_j value represents the one with the greatest level of contribution to the decision-making process:

$$\boldsymbol{w_j}=\frac{\sigma_j D_j}{\sum_{j=1}^{N}\left(\sigma_j D_j\right)}; (\boldsymbol{j}=\boldsymbol{1},\boldsymbol{2},\dots,\boldsymbol{N}), \tag{5}$$

herein, $w_j \in [0,1]$ is the j^{th} criterion weight value in the criteria weighting vector $\left(w = \left(w_1, w_2, \dots, w_j, \dots, w_N\right)\right)$ and the constraint as $\sum_{j=1}^{N} w_j = 1$.

3.2 Alternative Ranking using two-step Logarithmic Normalization Method

The ARLON method is an alternative ranking approach based on the aggregation of two logarithmic normalizations [11]. In this method, benefit-based and cost-based criteria are evaluated separately, and the final ranking of alternatives is obtained through their aggregation. During this aggregation process, the ratio of the number of benefit-based criteria to the total number of criteria, as well as the ratio of the number of cost-based criteria to the total number of criteria, are considered. ARLON consists of six steps, which are outlined as follows:

Step 1*:* The initial decision matrix $\left(X = \left[X_{ij}\right]_{MN}\right)$ defined in the CRISUS method is also utilized within the ARLON method. However, this matrix must not contain zero or negative values, since the ARLON procedure involves logarithmic operations.

Step 2*:* In the second step, two distinct logarithmic normalization procedures are applied. The first logarithmic normalization $\left(L^{1st} = \left[L_{ij}^{1st}\right]_{MN}\right)$ is performed using Eq. (6), while the second $\left(L^{2nd} = \left[L_{ij}^{2nd}\right]_{MN}\right)$ is applied using Eq. (7). Logarithmic normalization is preferred to mitigate the influence of large values in the initial matrix and to standardize the data. The use of two separate logarithmic normalization procedures allows for the aggregation of normalized values, resulting in more robust normalized data and facilitating subsequent sensitivity analyses:

$$\boldsymbol{L_{ij}^{1st}} = \begin{cases} \dfrac{\boldsymbol{ln}(\boldsymbol{X_{ij}})}{\boldsymbol{ln}\left(\prod_{i=1}^{M} \boldsymbol{X_{ij}}\right)} \ \textbf{for}\ \boldsymbol{j} \in \boldsymbol{C}^{+} \\ \dfrac{\boldsymbol{1} - \dfrac{\boldsymbol{ln}(\boldsymbol{X_{ij}})}{\boldsymbol{ln}\left(\prod_{i=1}^{M} \boldsymbol{X_{ij}}\right)}}{\boldsymbol{M-1}} \ \textbf{for}\ \boldsymbol{j} \in \boldsymbol{C}^{-} \end{cases} ; (\boldsymbol{i} = \boldsymbol{1}, \boldsymbol{2}, \dots, \boldsymbol{M};\ \boldsymbol{j} = \boldsymbol{1}, \boldsymbol{2}, \dots, \boldsymbol{N}), \tag{6}$$

$$\boldsymbol{L_{ij}^{2nd}} = \begin{cases} \dfrac{\boldsymbol{log_2}(\boldsymbol{X_{ij}})}{\sum_{i=1}^{M}\left(\boldsymbol{log_2}(\boldsymbol{X_{ij}})\right)} \ \textbf{for}\ \boldsymbol{j} \in \boldsymbol{C}^{+} \\ \boldsymbol{1} - \dfrac{\boldsymbol{log_2}(\boldsymbol{X_{ij}})}{\sum_{i=1}^{M}\left(\boldsymbol{log_2}(\boldsymbol{X_{ij}})\right)} \ \textbf{for}\ \boldsymbol{j} \in \boldsymbol{C}^{-} \end{cases} ; (\boldsymbol{i} = \boldsymbol{1}, \boldsymbol{2}, \dots, \boldsymbol{M};\ \boldsymbol{j} = \boldsymbol{1}, \boldsymbol{2}, \dots, \boldsymbol{N}). \tag{7}$$

Step 3: In the third step, the logarithmical normalized matrices are aggregated by using Heron Mean (Eq. (8)). The β parameter is used in this process. This parameter represents the contribution of the arithmetic mean, while $1-\beta$ indicates the contribution of the geometric mean of the logarithmical normalized matrices in the calculation of the aggregated normalized matrix $\left(L = \left[L_{ij}\right]_{MN}\right)$. Typically, β is set to 0.5 to ensure that both averages procedures are considered equally important. Other values of β, ranging between 0 and 1, can be used for sensitivity analysis:

$$\boldsymbol{L_{ij}} = \left((\boldsymbol{1}-\boldsymbol{\beta})\sqrt{\left(\boldsymbol{L_{ij}^{1st}}\right)\left(\boldsymbol{L_{ij}^{2nd}}\right)}\right) + \left((\boldsymbol{\beta})\frac{\left(\boldsymbol{L_{ij}^{1st}} + \boldsymbol{L_{ij}^{2nd}}\right)}{\boldsymbol{2}}\right); (\boldsymbol{i} = \boldsymbol{1}, \boldsymbol{2}, \dots, \boldsymbol{M};\ \boldsymbol{j} = \boldsymbol{1}, \boldsymbol{2}, \dots, \boldsymbol{N}). \tag{8}$$

Step 4*:* In this step, the criterion weight vector $\left(w = \left[w_j\right]_N\right)$ obtained from the CRISUS method is multiplied by the aggregated normalized matrix (Eq. (9)). As a result, the weighted aggregated matrix $\left(K = \left[K_{ij}\right]_{MN}\right)$ is obtained, reflecting the contribution of each criterion to the decision-making process:

$$\boldsymbol{K_{ij} = w_j * L_{ij}; (i = 1, 2, \dots, M;\ j = 1, 2, \dots, N).} \tag{9}$$

***Step 5**:* In this step, to determine the alternative ranking values, the cost-based and benefit-based criteria for each alternative are summed separately using Eq. (10) and Eq. (11), respectively. This procedure allows for the identification of criteria that positively and negatively influence the decision-making process. As a result, the total vector of cost-based criteria $(R^- = [R_i^-]_M)$ and the total vector of benefit-based criteria $(R^+ = [R_i^+]_M)$ are obtained:

$$\boldsymbol{R_i^- = \sum_{j=1}^{N^-} K_{ij}\ \mathbf{for}\ j \in C^-; (i = 1, 2, \dots, M),} \tag{10}$$

$$\boldsymbol{R_i^+ = \sum_{j=1}^{N^+} K_{ij}\ \mathbf{for}\ j \in C^+; (i = 1, 2, \dots, M).} \tag{11}$$

***Step 6**:* In the final step, the alternative ranking scores vector $(R = [R_i]_M)$ are calculated by using Eq. (12). The total vector of cost-based criteria and the total vector of benefit-based criteria are aggregated in this step. The ϕ parameter represents the ratio of the number of benefit-based criteria to the total number of criteria, aiming to maximize the benefit level. When the number of benefit-based criteria is higher, the influence of the total vector of benefit-based criteria becomes more significant. Consequently, the alternative with the highest R_i value is considered the best alternative, whereas the one with the lowest R_i value is regarded as the least favorable alternative.

$$\boldsymbol{R_i = (R_i^-)^{(1-\phi)} + (R_i^+)^{(\phi)}; (i = 1, 2, \dots, M).} \tag{12}$$

4. Empirical Study: Sustainability Performance Evaluation of Turkish Airlines

Table 2 provides the code for the criteria sets. Turkish Airlines was founded in 1933 as the State Airlines Administration and in 1955 adopted its current name and joined the International Air Transport Association (IATA). It has continued its growth since the 1980s by increasing its international flights. During this period, passenger numbers, employee capacity, and digital services have significantly improved. It launched the Miles&Smiles program in 2000 and strengthened its global network by becoming a member of the Star Alliance in 2008. The catering services offered in collaboration with Do&Co have contributed to improving service quality. It has improved its service quality through fleet investments and global growth strategies. Operating from its hub at Istanbul Airport, the company has become one of the world's leading airlines with its extensive fleet and flight network [25].

Turkish Airlines has a wide global flight network, operating flights to three hundred fifty-two destinations in a hundred thirty-one countries. It enhances its international connections through its Star Alliance membership and codeshare agreements [26]. It increased its fleet investments, raising the number of aircraft to four hundred nighty-two in 2024. The increase in the share of next-generation aircraft supports the company's sustainability and efficiency goals [27].

Turkish Airlines is among the world's leading airlines thanks to its extensive fleet and global flight network. It holds a strong position ahead of many competitors in terms of the number of international destinations [28]. Türkiye's strategic location and Istanbul's central role provide Turkish Airlines with a significant advantage in intercontinental air transportation [29]. It was selected as Europe's Best Airline in the 2025 Skytrax World Airline Awards and received significant awards for service quality [30]. It has achieved a strong position in the global aviation sector in recent years thanks to its rapid growth and customer-focused approach [31,32]. It has also become a full-service airline offering comprehensive services. The company prioritizes sustainability efforts alongside financial and operational improvements. It is reducing its environmental impact within the scope of its 2050 carbon neutrality target through more efficient aircraft, fuel-saving practices, and sustainable fuel initiatives [33].

Table 2
Codes for the criteria applied at each phase

Code	Criteria	Type
	Phase 1: Economic Performance	
C_1	Net Revenue (USD Million)	Benefit
C_2	EBITDAR (USD Million)	Benefit
C_3	EBITDAR Margin (%)	Benefit
C_4	Net Debt	Cost
C_5	Total Assets	Benefit
C_6	Total Investments	Benefit
C_7	Return on Equity (%)	Benefit
C_8	Total Flight Miles (Nautical Mile)	Benefit
C_9	Flight Destinations	Benefit
C_{10}	Cargo & Mail Carried (Ton)	Benefit
C_{11}	Fleet Average Age	Cost
C_{12}	Total Number of Aircraft	Benefit
C_{13}	R&D Expenditure (USD Million)	Benefit
	Phase 2: Social Performance	
C_{14}	Number of Employees on Maternity/Paternity Leave	Benefit
C_{15}	Employee Trainings- Participants (Number)	Benefit
C_{16}	Accident Frequency Rate (by 1,000,000 Working Hours)	Cost
C_{17}	Absentee Rate (Total) (% of total days scheduled)	Cost
C_{18}	OHS Trainings- Number of Participants	Benefit
C_{19}	Number of Disaster Emergency Trainings (Number)	Benefit
C_{20}	Number of Disaster Emergency Drills	Benefit
C_{21}	Number of Employees Receiving Child Care/Elderly Care Support	Benefit
C_{22}	Number of Employees/Managers Receiving Training	Benefit
C_{23}	Customer Satisfaction Rate (%)	Benefit
C_{24}	Flight Safety Trainings	Benefit
C_{25}	SAFA Rate (%)	Cost
	Phase 3: Environmental Performance	
C_{26}	Total Energy Consumption (GJ)	Cost
C_{27}	Fuel Efficiency (Fuel Consumption per 100 Available Seat KM) (Liters/100 ASK)	Cost
C_{28}	Total Greenhouse Gas Emissions (ton CO2 e)	Cost
C_{29}	Greenhouse Gas Emission Savings Provided by Efficiency Projects (tons CO2e)	Benefit
C_{30}	Passenger Flight Offset (number)	Benefit
C_{31}	NOx Emissions (ton)	Cost
C_{32}	Total Water Withdrawal (m3)	Cost
C_{33}	Solid Wastes (ton)	Cost
C_{34}	Environmental Management Expenditure (USD Million)	Benefit
C_{35}	Number of GHG Awareness Training Participants	Benefit

This empirical research analyzes Turkish Airlines' sustainability practices and operational performance over the past five years to evaluate sustainability performance in the aviation sector. Furthermore, this research evaluates Turkish Airlines' sustainability performance between 2019 and 2023 in four phases, encompassing economic, social, and environmental dimensions. The empirical research is conducted in four phases. The *first phase* evaluates economic performance, the *second phase* evaluates social performance, and the *third phase* evaluates environmental performance. Finally, in the fourth phase, Turkish Airlines' overall sustainability performance is analyzed annually.

4.1 Phase 1: Economic Performance Evaluation of Turkish Airlines

Financial and operational performance are fundamental indicators of a firm's overall success. The effective utilization of assets serves as a measure of financial performance, reflecting a company's ability to generate maximum income. This concept provides insight into the firm's overall financial health over a specified period [34]. In the airline industry, financial performance plays a critical role in both short-term and long-term decision-making and directly informs strategic planning. A comprehensive evaluation of financial performance necessitates the analysis of key metrics related to profitability, liquidity, and solvency. In this phase, thirteen economical indicators are considered as performance indicators. These indicators are generally used for corporate financial performance analysis [35,36].

The economic performance of airline companies indicates their economic strength [37]. In this context, financial ratios obtained from the financial statements of the airline company are used as economic indicators [38,39]. In the first phase, the economic performance of Turkish airlines is determined using the CRISUS-ARLON model with thirteen economic criteria. In the first step (*Step 1-1*) of the CRISUS-ARLON model for the first stage, financial ratios for thirteen economic indicators were determined based on data obtained from financial statements. These values represent the initial matrix $\left(X = \left[X_{ij}\right]_{MN}\right)$ for calculating economic performance and are shown in Table 3.

Table 3
Initial matrix for economic performance (Phase 1)

Criteria	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}	C_{12}	C_{13}
2019	13,229	3107	23.50	10,107	24,724	4315	11.0	500.10	322	1,544,341	8.33	350	7,691,853
2020	6734	1866	27.70	46,005	25,530	4903	16.0	254.97	324	1,494,276	8.44	363	8,857,844
2021	10,686	3744	35.0	11,596	26,537	4193	14.0	379.95	333	1,880,989	8.50	370	4,254,596
2022	18,426	5377	29.20	8714	30,944	5499	32.87	515.50	342	1,679,393	8.70	394	8,611,503
2023	20,942	6077	29.0	12,236	35,671	20,941	47.60	582.90	345	1,658,686	9.30	440	10,903,014

In the second step, the first normalized matrix $\left(Z = \left[Z_{ij}\right]_{MN}\right)$ (Table A1 in Appendix) was calculated (Eq. (2)) using vector normalization. In the third step, the second normalized matrix $\left(G = \left[G_{ij}\right]_{MN}\right)$ (Table A2) was obtained (Eq. (3)) using linear normalization. In the fourth step, the distance vector $\left(D = \left[D_j\right]_N\right)$ (Table A3) was calculated (Eq. (4)) using this normalized matrix. In the fifth step, the standard deviation vector $\left(\sigma = \left[\sigma_j\right]_N\right)$ (Table A3) was calculated using the vector normalized matrix. In the sixth step (*Step 1-6*), the criterion weight vector $\left(w = \left[w_j\right]_N\right)$ was determined (Eq. (4)) using the standard deviation and distance vectors and is presented in Table 4. The top three most influential criteria were determined to be Total Investments (C_6), Net Debt (C_4), and Return on Equity (%) (C_7). This indicates that financial metrics play a more critical role than operational indicators in evaluating economic performance.

Table 4
Criterion weight vector for economic performance (Phase 1)

Criteria	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}	C_{12}	C_{13}
w_j	0.0909	0.0939	0.0299	0.1721	0.0336	0.2448	0.1535	0.0624	0.0064	0.0189	0.0093	0.0193	0.0649
Rank	5th	4th	9th	2nd	8th	1st	3rd	7th	13th	11th	12th	10th	6th

In the second stage of the CRISUS-ARLON model, the first logarithmic normalization matrix $\left(L^{1st} = \left[L_{ij}^{1st}\right]_{MN}\right)$ (Table A4) and the second logarithmic normalization matrix $\left(L^{2nd} = \left[L_{ij}^{2nd}\right]_{MN}\right)$ (Table A5) were calculated (Eq. (6) and Eq. (7)) using the initial matrix. These matrices were then aggregated (Eq. (8)) $(\beta = 0.5)$ to calculate the aggregated normalized matrix $\left(L = \left[L_{ij}\right]_{MN}\right)$ (Table A6). Using the criterion weights, this weighted aggregated matrix $\left(K = \left[K_{ij}\right]_{MN}\right)$ (Table A7) was determined (Eq. (9)). The cost-based criteria vector $(R^- = [R_i^-]_M)$ (Table A8) and the benefit-based criteria vector $(R^+ = [R_i^+]_M)$ (Table A8) were calculated separately (Eq. (10) and Eq. (11)). In the final step, since eleven of the thirteen criteria are benefit-based, the parameter (ϕ) was set to 0.8461. Using ϕ parameter, Turkish Airlines' economic performance $(R = [R_i]_M)$ for the period 2019-2023 was determined (Eq. (12)) on a yearly basis and is shown in Table 5. Looking at the economic performance, it was found that economic performance was low during the COVID-19 period and improved over the years.

Table 5
Economic performance levels of Turkish Airlines for the 2019–2023 period (Phase 1)

Year	2019	2020	2021	2022	2023
R_i	0.8870	0.8843	0.8890	0.9043	0.9170
Rank	4th	5th	3rd	2nd	1st

4.1.1 Robustness analyses for economic performance assessment

The CRISUS-ARLON hybrid method facilitates the ranking of alternatives by integrating two different logarithmic normalization approaches through aggregation with the Heron mean. Within the Heron mean, the parameter β (ranging between 0 and 1) determines the contribution level of the arithmetic mean relative to the geometric mean. In this phase, the β parameter was set to 0.5, thereby balancing the effects of first and second logarithmic normalization in the year-based economic performance evaluation process.

To support the robustness of the results, sensitivity analysis was performed by assigning the β parameter to values between 0 and 1 (Figure 2). The results show that while performance values differ when the β value changes, the economic performance ranking remains the same. This indicates that Turkish Airlines' economic performance results for the 2019-2023 period are consistent and reliable under different parameter values.

4.1.2 Comparative analyses for economic performance assessment

Using the CRISUS-ARLON hybrid method, the economic performance levels of Turkish Airlines for the 2019–2023 period were determined in this study.

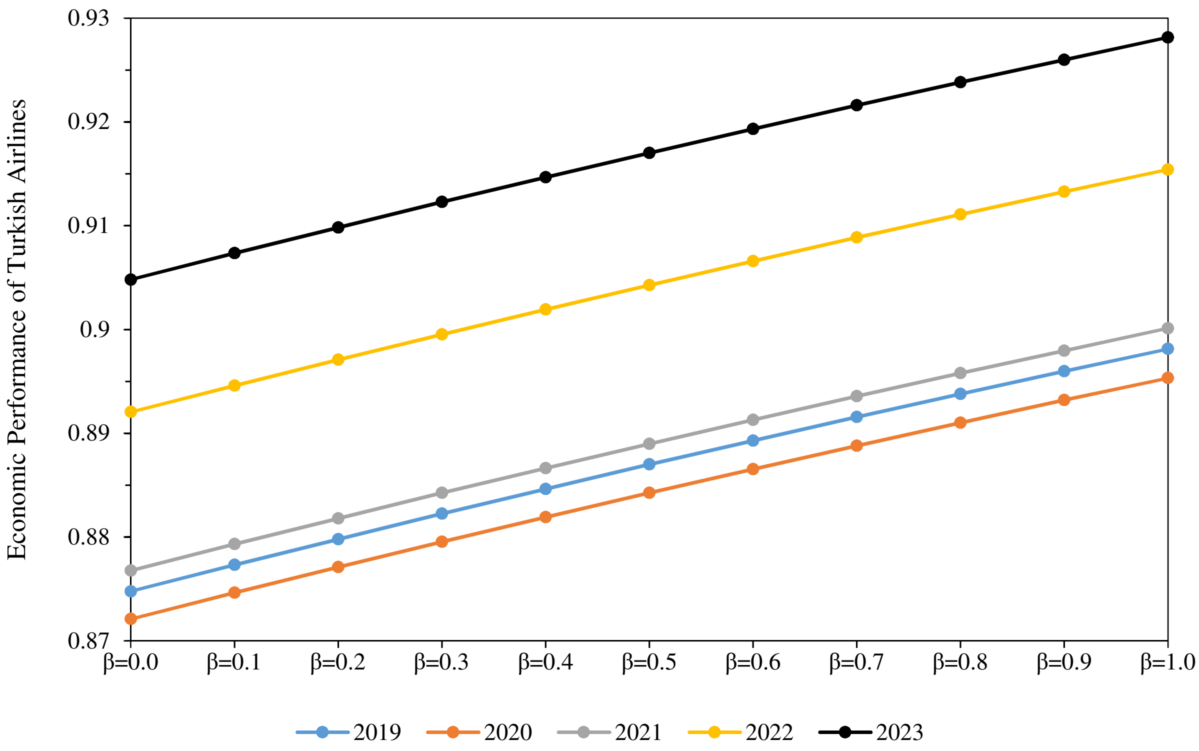

Fig. 2. Sensitivity analysis for economic performance (Phase 1)

To verify the consistency of these year-based economic performance results, several alternative ranking methods from the literature (namely AROMAN, ARTASI, MABAC, MARCOS, RAM, SAW, TOPSIS, and WASPAS) were also applied, and the outcomes are illustrated in Figure 3.

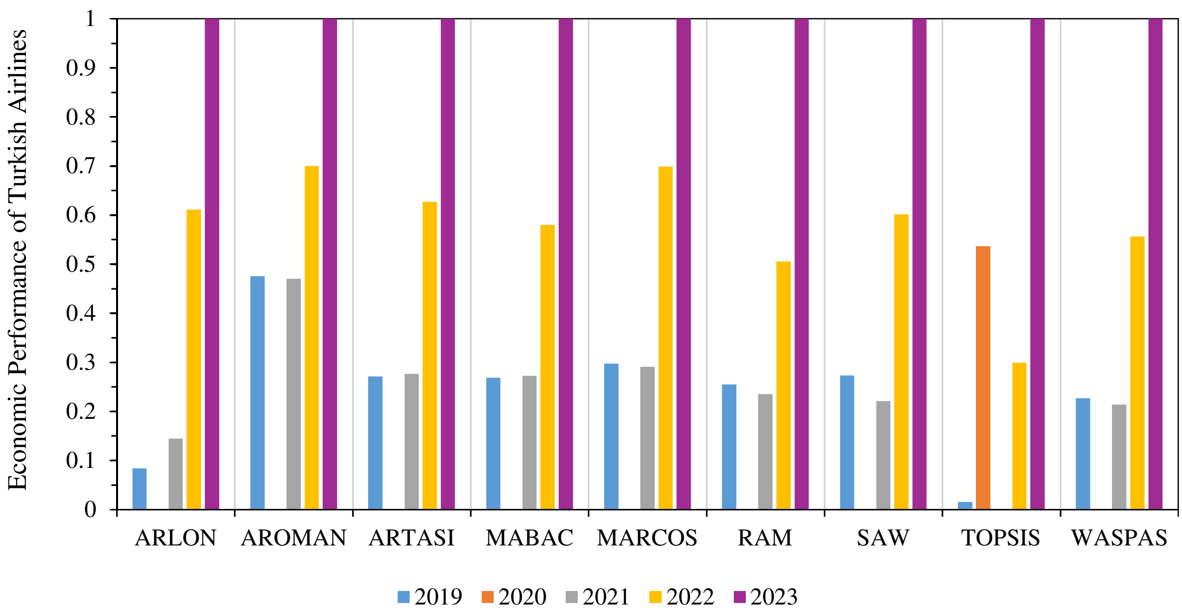

Fig. 3. Comparative analysis for economic performance (Phase 1)

For the sake of standardization, the criterion weight vector obtained through the CRISUS weighting method was employed across all methods. Furthermore, to render the economic performance results comparable, the max–min normalization technique was applied. The correlation relationships among the methods are presented in Table 6. The highest correlation was observed between ARLON and WASPAS (0.9863). In addition, it was found that all correlation values exceeded 0.70, indicating strong positive relationships among the methods. These findings confirm that the results obtained are consistent and reliable.

Table 6
Correlation analysis among the methods (Phase 1)

Methods	ARLON	AROMAN	ARTASI	MABAC	MARCOS	RAM	SAW	TOPSIS	WASPAS
ARLON	1	0.9010	0.9816	0.9784	0.9775	0.9724	0.9823	0.7104	0.9863
AROMAN		1	0.9659	0.9639	0.9690	0.9493	0.9561	0.3891	0.9459
ARTASI			1	0.9986	0.9972	0.9913	0.9980	0.6015	0.9963
MABAC				1	0.9922	0.9966	0.9977	0.6180	0.9980
MARCOS					1	0.9793	0.9939	0.5629	0.9884
RAM						1	0.9937	0.6578	0.9970
SAW							1	0.6302	0.9981
TOPSIS								1	0.6635
WASPAS									1

4.2 Phase 2: Social Performance Evaluation of Turkish Airlines

Social performance indicators capture the development and implementation of health and safety policies, equal employment opportunities, and stakeholder-related initiatives. These indicators are employed by stakeholders to assess a company's operational effectiveness and overall financial health. Furthermore, they provide managers with critical insights to enhance decision-making regarding operational efficiency, enabling organizations to maintain adaptability and resilience during crises [40].

Social sustainability performance reflects the extent to which a company achieves its social objectives, encompassing dimensions such as working conditions, health and safety, employee relations, wellness, diversity, human rights, fair labor practices, community engagement, and philanthropic activities. Investments in occupational health and safety can increase employee motivation and support workforce productivity [41]. Furthermore, social performance contributes to the company's reputation and sustainable success by increasing stakeholder trust through good governance practices [39].

In Phase 2, twelve social indicators are identified to assess social performance. These social metrics are widely utilized for evaluating overall corporate performance [42]. The social performance levels of Turkish airlines were calculated on a yearly basis using the CRISIS-ARLON model. The initial matrix for social performance analysis is shown in Table 7.

Table 7
Initial matrix for social performance (Phase 2)

Criteria	C_{14}	C_{15}	C_{16}	C_{17}	C_{18}	C_{19}	C_{20}	C_{21}	C_{22}	C_{23}	C_{24}	C_{25}
2019	1718	410,210	12.69	2.69	14,951	24	58	2413	4863	75	12,226	17.70
2020	1354	358,637	4.57	1.47	20,563	10	8	2912	2236	77	13,595	31.80
2021	1231	378,148	7.82	1.97	153,579	19	97	2922	6207	83	45,729	5.40
2022	296	468,596	14.36	3.36	91,104	48	96	3000	5113	83	13,649	14.30
2023	998	694,480	16.26	3.64	173,319	49	91	3554	7146	81	12,563	25.60

After applying the CRISUS steps, the social criterion weight vector was determined and is presented in Table 8. The top three most influential criteria were determined to be OHS Trainings-

Number of Participants (C_{18}), Flight Safety Trainings (C_{24}), and Number of Disaster Emergency Trainings (C_{19}). This indicates that safety metrics play a more critical role than the others. Contrary to expectations, the Customer Satisfaction Rate (C_{23}) was identified as the criterion with the lowest significance. This finding reveals that, in the assessment of Turkish Airlines' social performance, safety-oriented activities hold greater importance than customer satisfaction.

Table 8
Criterion weight vector for social performance (Phase 2)

Criteria	C_{14}	C_{15}	C_{16}	C_{17}	C_{18}	C_{19}	C_{20}	C_{21}	C_{22}	C_{23}	C_{24}	C_{25}
w_j	0.0874	0.0520	0.0741	0.0596	0.1696	0.1130	0.1034	0.0235	0.0647	0.0078	0.1536	0.0913
Rank	6th	10th	7th	9th	1st	3rd	4th	11th	8th	12th	2nd	5th

Subsequently, by following the steps of the ARLON method, the social performance levels of Turkish airlines for the period 2019-2023 were determined and are presented in Table 9. The airline's highest social performance was recorded in 2021. Furthermore, during the COVID-19 period (2019–2020), social performance was comparatively lower than in other years.

Table 9
Social performance levels of Turkish Airlines for the 2019–2023 period (Phase 2)

Year	2019	2020	2021	2022	2023
R_i	0.8040	0.7916	0.8299	0.8133	0.8153
Rank	4th	5th	1st	3rd	2nd

4.2.1 Robustness analyses for social performance assessment

To validate the robustness of the results for social performance, a sensitivity analysis was performed by varying the β parameter across the interval from 0 to 1. The results of this analysis are illustrated in Figure 4.

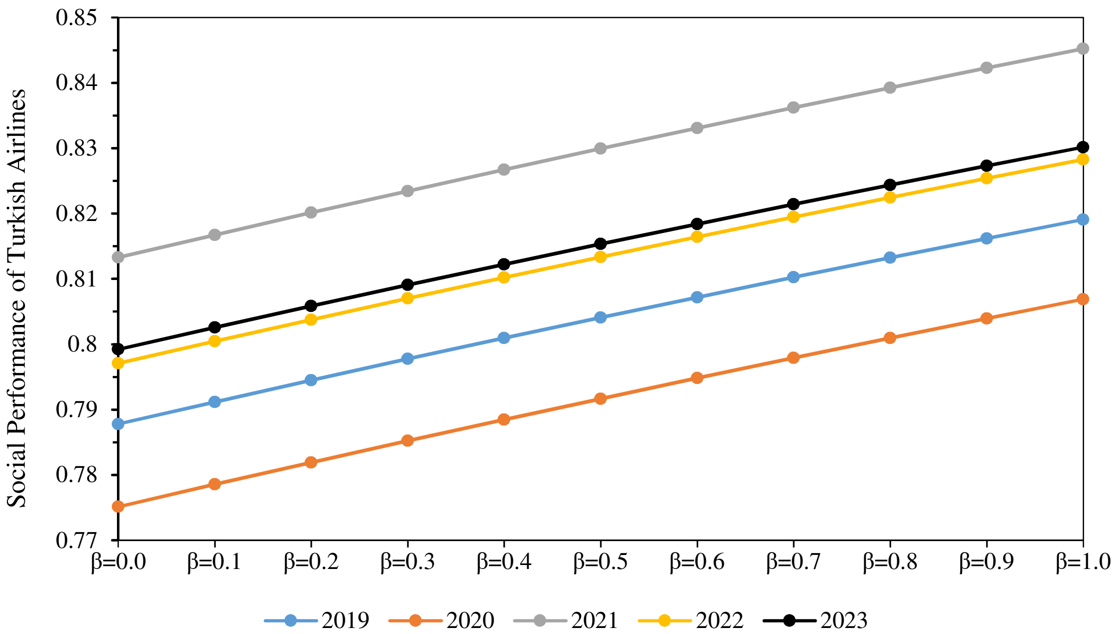

Fig. 4. Sensitivity analysis for social performance (Phase 2)

The social performance values of Turkish Airlines during the 2019–2023 period are shown to be consistent and resilient across different aggregation scenarios, confirming the reliability of CRISUS-ARLON in evaluating non-financial performance dimensions.

4.2.2 Comparative analyses for social performance assessment

The result of the comparison analyzes are shown in Figure 5. According to the CRISUS-ARLON hybrid method, 2021 was the most successful year in Turkish Airlines' social performance during the 2019-2023 period. Comparative analysis results show that all methods except the RAM method identified 2021 as the best performing year.

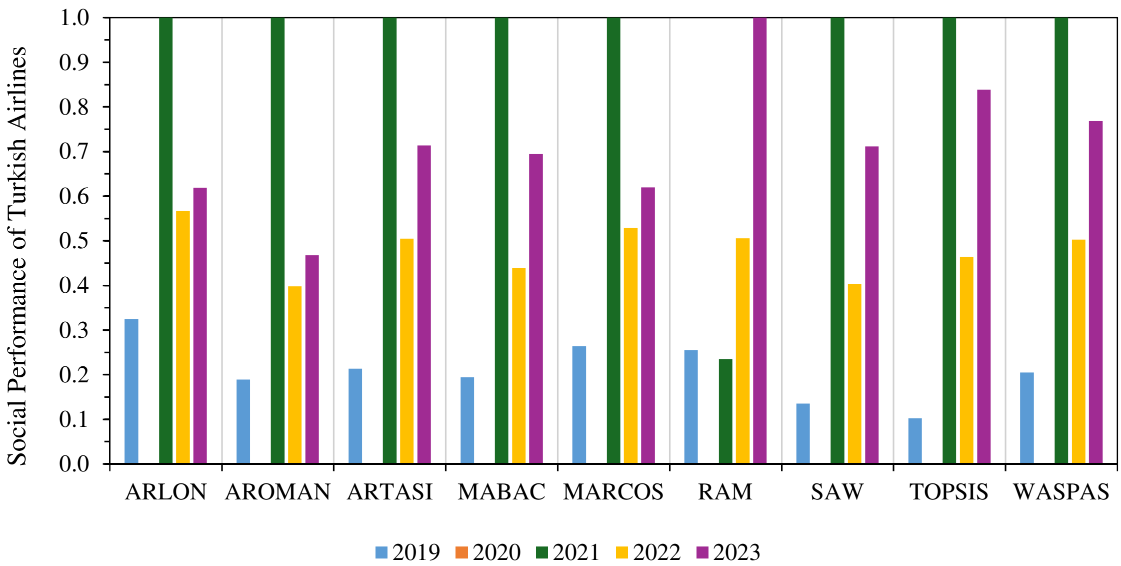

Fig. 5. Comparative analysis for social performance (Phase 2)

Correlation analysis (Table 10) revealed strong relationships between ARLON and the other methods (except RAM). These findings demonstrate that the CRISUS-ARLON hybrid method produces reliable and consistent results in social performance evaluation.

Table 10
Correlation analysis among the methods (Phase 2)

Methods	ARLON	AROMAN	ARTASI	MABAC	MARCOS	RAM	SAW	TOPSIS	WASPAS
ARLON	1	0.9750	0.9818	0.9747	0.9973	0.3920	0.9578	0.9330	0.9704
AROMAN		1	0.9644	0.9693	0.9824	0.2302	0.9594	0.9174	0.9488
ARTASI			1	0.9977	0.9912	0.4771	0.9931	0.9842	0.9982
MABAC				1	0.9869	0.4504	0.9977	0.9846	0.9962
MARCOS					1	0.3939	0.9749	0.9525	0.9819
RAM						1	0.4589	0.560	0.5202
SAW							1	0.9911	0.9942
TOPSIS								1	0.9919
WASPAS									1

4.3 Phase 3: Environmental Performance Evaluation of Turkish Airlines

The aviation sector faces significant challenges in terms of environmental sustainability, particularly due to aircraft emissions [43]. The aviation sector has also significant environmental impacts due to its use of fossil fuels. Noise, emissions, water pollution, and waste are the sector's primary environmental concerns. Moreover, aviation activities can cause water pollution, and terminal and flight services generate significant amounts of waste [44]. In this phase, ten key indicators are identified to evaluate environmental performance. These metrics are widely used to assess the environmental performance of companies within the aviation sector.

The CRISUS-ARLON model steps were applied within the environmental performance analysis. The initial matrix for the environmental performance analysis is shown in Table 11.

Table 11
Initial matrix for environmental performance (Phase 3)

Criteria	C_{26}	C_{27}	C_{28}	C_{29}	C_{30}	C_{31}	C_{32}	C_{33}	C_{34}	C_{35}
2019	247,848,257	3.26	17,877,124	179,740	686	61,846	64,903	1577	8,211,709	3965
2020	126,067,694	3.21	9,094,999	72,312	669	31,398	38,022	1269	11,477,784	2522
2021	187,326,898	3.16	16,591,244	117,815	672	46,678	255,238	1608	8,433,014	1487
2022	252,648,196	3.10	22,983,093	182,987	476	63,040	364,508	2313	20,062,805	3586
2023	289,961,238	3.07	27,464,369	228,264	694	72,384	206,595	2170	16,827,066	12,903

The CRISUS steps were applied, and the environmental performance criterion weight vector was obtained and is presented in Table 12. The top three most influential criteria were determined to be the Number of GHG Awareness Training Participants (C_{35}), Total Water Withdrawal (m3) (C_{32}), and Environmental Management Expenditure (USD Million) (C_{34}). This indicates that expenditure, training, and water withdrawal metrics play a more critical role than greenhouse gas emissions. This result indicates that, rather than carbon dioxide emissions, criteria related to training, expenditure, and wastewater management provide a greater contribution to the determination of environmental performance levels in airlines. Furthermore, contrary to expectations, Fuel Efficiency (Fuel Consumption per 100 Available Seat KM) (Liters/100 ASK) (C_{27}) was identified as the parameter with the lowest level of influence in assessing environmental performance.

Table 12
Criterion weight vector for environmental performance (Phase 3)

Criteria	C_{26}	C_{27}	C_{28}	C_{29}	C_{30}	C_{31}	C_{32}	C_{33}	C_{34}	C_{35}
w_j	0.0708	0.0059	0.0895	0.1001	0.0350	0.0710	0.1699	0.0594	0.1037	0.2946
Rank	7th	10th	5th	4th	9th	6th	2nd	8th	3rd	1st

Subsequently, the environmental performance levels of Turkish airlines for the period 2019-2023 were determined by applying the ARLON methodology steps and are shown in Table 13. The airline's highest environmental performance was recorded in 2023. Furthermore, during the COVID-19 period (2019–2020), environmental performance was comparatively lower than in other years.

Table 13
Environmental performance levels of Turkish Airlines for the 2019–2023 period (Phase 3)

Year	2019	2020	2021	2022	2023
R_i	0.8025	0.7982	0.7883	0.7989	0.8142
Rank	2nd	4th	5th	3rd	1st

4.3.1 Robustness analyses for environmental performance assessment

To assess the robustness of the results for environmental performance, a sensitivity analysis was carried out by varying the β parameter within the range of 0 to 1. The outcomes of this analysis are presented in Figure 6. The results indicate that when $\beta = 0$, corresponding to exclusive reliance on the geometric mean, the environmental performance values are relatively lower, although the ranking of the alternatives remains unchanged. In contrast, when $\beta = 1$, reflecting complete reliance on the arithmetic average, the performance values are comparatively higher, yet the ordering of the alternatives is again preserved. More broadly, the analysis reveals that increasing the contribution of the arithmetic average produces higher performance values, while the relative ranking of alternatives is unaffected.

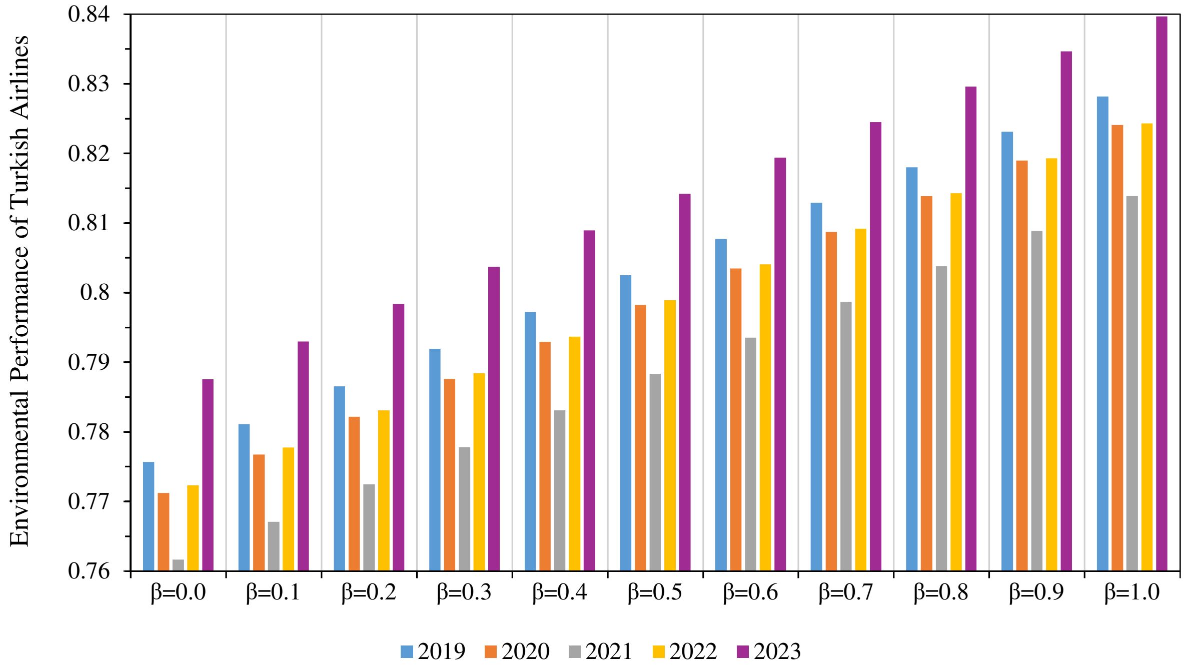

Fig. 6. Sensitivity analysis for social performance (Phase 3)

In summary, the environmental performance values of Turkish Airlines for the 2019–2023 period demonstrate stability and consistency under different aggregation conditions, thereby reinforcing the robustness of the CRISUS-ARLON hybrid method in evaluating sustainability-related performance indicators.

4.3.2 Comparative analyses for environmental performance assessment

The environmental performance of Turkish Airlines for the period 2019–2023 was assessed using CRISUS-ARLON. According to the results of this approach, the year 2023 demonstrated the highest environmental performance. In the comparative analysis conducted with eight alternative ranking methods, four methods (AROMAN, RAM, TOPSIS, WASPAS) similarly identified 2023 as the best-performing year, while the other four methods (ARTASI, MABAC, MARCOS, SAW) indicated 2020 as the year with the highest environmental performance. The comparative results are illustrated in Figure 7.

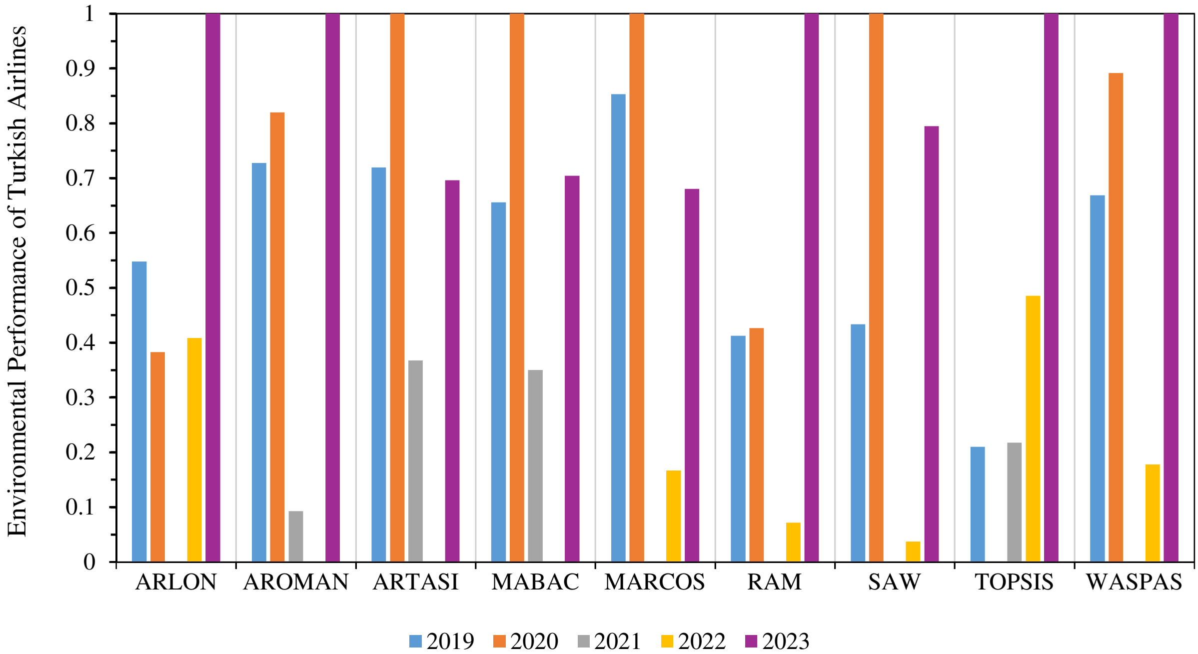

Fig. 7. Comparative analysis for environmental performance (Phase 3)

The correlation analysis of environmental performance values across methods is presented in Table 14. The strongest correlation was observed between ARLON and RAM (0.9195), whereas the weakest correlation was found between ARLON and ARTASI (0.3095). Furthermore, the correlations between ARLON and MABAC were at a moderate level, while its correlations with AROMAN, MARCOS, SAW, TOPSIS, and WASPAS all exceeded 0.50, indicating relatively strong associations. Compared to the economic and social performance stages, the comparative analyses in the environmental performance stage yielded relatively lower consistency across methods. Nevertheless, the generally satisfactory levels of correlation support the conclusion that the environmental performance assessments, as well as CRISUS-ARLON itself, produce consistent and reliable results.

Table 14
Correlation analysis among the methods (Phase 3)

Methods	ARLON	AROMAN	ARTASI	MABAC	MARCOS	RAM	SAW	TOPSIS	WASPAS
ARLON	1	0.7334	0.3095	0.3257	0.5335	0.9195	0.5767	0.7528	0.7875
AROMAN		1	0.8716	0.8764	0.8825	0.8960	0.9112	0.2337	0.9709
ARTASI			1	0.9971	0.8742	0.5859	0.8838	-0.2329	0.8072
MABAC				1	0.8665	0.6068	0.9080	-0.2020	0.8217
MARCOS					1	0.6354	0.8920	-0.1380	0.9036
RAM						1	0.7609	0.6390	0.8934
SAW							1	0.0541	0.9463
TOPSIS								1	0.2640
WASPAS									1

4.4 Phase 4: Sustainability Performance of Turkish Airlines

In the fourth phase, sustainability performance is determined by calculating the average of economic, social, and environmental performance scores. Table 15 presents the economic, social, environmental, and overall sustainability performance levels of Turkish Airlines, along with their rankings, for the period 2019–2023 (Figure 8).

Table 15
Sustainability performance levels of Turkish Airlines for the 2019–2023 period (Phase 4)

Year	Economic Performance	Social Performance	Environmental Performance	Sustainability Performance	Rank
2019	0.8870	0.8040	0.8201	0.8370	4th
2020	0.8843	0.7916	0.8164	0.8308	5th
2021	0.8890	0.8299	0.8074	0.8421	3rd
2022	0.9043	0.8133	0.8164	0.8447	2nd
2023	0.9170	0.8153	0.8204	0.8509	1st

The findings reveal that the lowest sustainability performance occurred during the COVID-19 period, whereas the post-pandemic years demonstrate a consistent improvement in performance. Notably, the year 2023 represents the highest level of sustainability performance within the period analyzed.

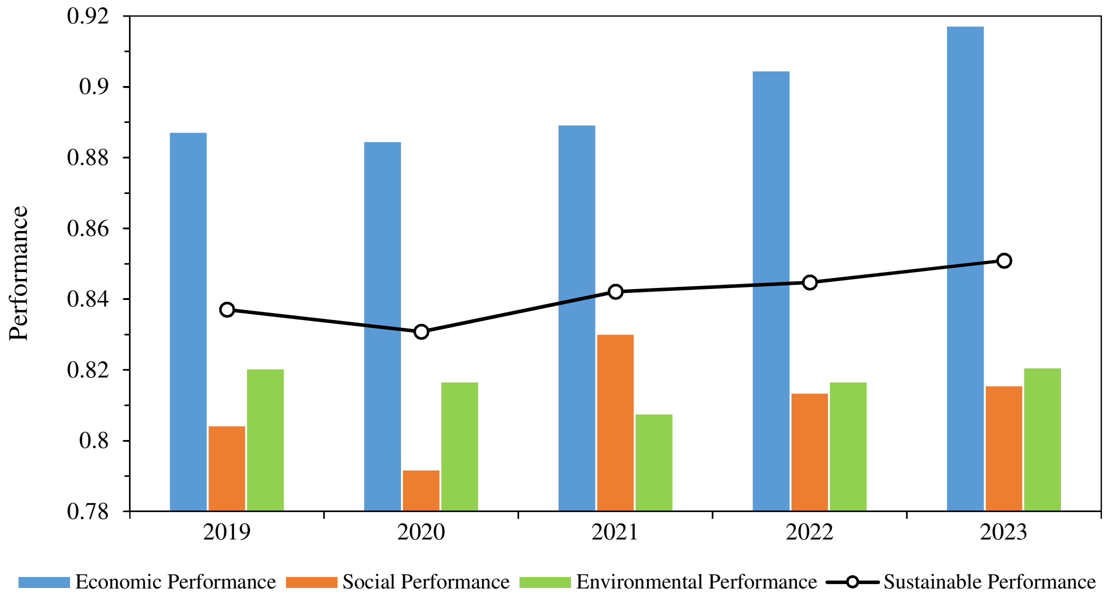

Fig. 8. Performance of Turkish Airlines for the 2019–2023 period

5. Results

This study investigated the economic, social, and environmental performance levels of an airline company over time using the CRISUS-ARLON hybrid method, with the subsequent determination of sustainability performance levels. Following the introduction of the proposed methodology, an application was carried out for Turkish Airlines covering the period 2019–2023.

5.1 Economic Performance

In the first phase, Turkish Airlines' economic performance for the years 2019-2023 was evaluated, criterion weights were calculated, and annual performance levels were determined. Among the thirteen economic criteria, Total Investment was identified as the most important criterion. In contrast, the number of flight destinations had the least impact, mainly because the change in this indicator was limited during the period examined. The results show that economic performance declined during the COVID-19 period, then steadily increased after the pandemic, reaching its highest level in 2023. This demonstrates the recovery process of the sector and the contribution of effective management to economic performance. Furthermore, robustness and sensitivity analyses confirmed the reliability of these results.

5.2 Social Performance

In second phase, Turkish Airlines' social performance was evaluated. Criterion weights were determined, and annual social performance levels were analyzed. Occupational health and safety were identified as the most important criterion among the social criteria. Training activities and the number of trained employees were among the important criteria affecting social performance. In contrast, customer satisfaction was determined to be the criterion with the least importance. Social performance peaked in 2021 but remained at a lower level during the pandemic. Furthermore, sensitivity and robustness analyses showed consistent results.

5.3 Environmental Performance

The results showed that budget allocations for environmental management and greenhouse gas awareness training programs were the most important criteria. The impact of fuel efficiency and fuel consumption was found to be lower than expected. This can be attributed to the reduction in fuel consumption due to technological advancements. The results also show that environmental performance declined in 2020, then increased steadily in subsequent years, reaching its peak in 2023. Furthermore, robustness and sensitivity analyses confirmed the reliability of the results.

5.4 Sustainability Performance

In the fourth phase, the overall sustainability performance was calculated by averaging the economic, social, and environmental performance scores. The results show that performance decreased during the pandemic years, then increased in subsequent years, reaching its highest level in 2023. The results show that the CRISUS-ARLON hybrid method is effective in evaluating the economic, social, environmental, and overall sustainability performance of airlines. Furthermore, robustness and comparative analyses confirm that the method produces reliable and consistent results.

6. Implications

This research offers various contributions to the evaluation of the sustainability performance of airline companies. Methodologically, the CRISUS-ARLON hybrid method is proposed for evaluating sustainability performance. Thus, companies and investors can benefit from the sustainability performance analysis of airline companies. Furthermore, the robustness of the CRISUS-ARLON model application results makes it a reliable model that can be used by performance trackers for performance monitoring. In terms of application, the method was applied to Turkish Airlines' data from 2019-2023, enabling a systematic evaluation of economic, social, and environmental performance. Total investment, the number of employees participating in occupational health and safety training, and the number of employees participating in greenhouse gas awareness training are the most influential factors on sustainability performance. Thus, the areas that strategy experts need to focus on from an economic, social, and environmental perspective have been identified. It also shows that sustainability performance significantly decreased during the COVID-19 period but improved in subsequent years with the recovery process. The study provides airline executives with a systematic decision-support framework for identifying areas for improvement in sustainability, planning resources more effectively, and developing strategies. Furthermore, the proposed model stands out as a flexible and reliable sustainability assessment method that can be applied to other airlines and transportation companies.

7. Conclusion

This paper develops and applies a CRISUS-ARLON model to Turkish Airlines to evaluate their sustainability performance. The proposed model was tested in four stages on Turkish Airlines data from 2019-2023. Economic, social, and environmental performances were evaluated separately. Then, overall sustainability performance was calculated. The results highlight the importance of investments, occupational health and safety, and greenhouse gas emissions. The impact of the COVID-19 pandemic was observed in all dimensions. While economic and environmental performance peaked in 2023, social performance peaked in 2021. This result aligns with the expectations of the airline industry. Sensitivity and comparison tests supported the robustness of the CRISUS-ARLON model in all dimensions.

As a first limitation of the research, the analysis only covers Turkish Airlines for the period 2019-2023. Further research on different periods and airlines is recommended. Since the raw data for the analysis was obtained from open-source reports, there may be limitations in data sources. Furthermore, financial ratio calculations may require expertise. The proposed model application requires computational expertise. The proposed model can be improved using fuzzy sets and criterion weighting approaches based on expert opinions. The research can be expanded by adding different parameters, and the results can be compared. The CRISUS-ARLON model can be used for sustainability performance analysis in different sectors.

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Conflicts of Interest
The author declares that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Declaration on the use of Artificial Intelligence Tools
During the preparation of this work the authors used Grammarly solely for language editing and proofreading. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Appendix: Supplementary Tables

Table A1
Vector normalization matrix (for Economic Performance)

Z_{ij}	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}	C_{12}	C_{13}
2019	0.3966	0.3222	0.3610	0.8010	0.3816	0.1876	0.1757	0.4846	0.4320	0.4168	0.5699	0.4069	0.4119
2020	0.2019	0.1935	0.4255	0.0941	0.3941	0.2132	0.2556	0.2471	0.4347	0.4033	0.5642	0.4220	0.4743
2021	0.3204	0.3882	0.5376	0.7716	0.4096	0.1823	0.2236	0.3682	0.4468	0.5077	0.5611	0.4301	0.2278
2022	0.5524	0.5576	0.4485	0.8284	0.4776	0.2391	0.5251	0.4995	0.4588	0.4533	0.5508	0.4580	0.4611
2023	0.6278	0.6302	0.4455	0.7590	0.5506	0.9105	0.7603	0.5648	0.4629	0.4477	0.5198	0.5115	0.5838

Table A2
The linear normalization matrix (for Economic Performance)

G_{ij}	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}	C_{12}	C_{13}
2019	0.3966	0.3222	0.3610	0.8010	0.3816	0.1876	0.1757	0.4846	0.4320	0.4168	0.5699	0.4069	0.4119
2020	0.2019	0.1935	0.4255	0.0941	0.3941	0.2132	0.2556	0.2471	0.4347	0.4033	0.5642	0.4220	0.4743
2021	0.3204	0.3882	0.5376	0.7716	0.4096	0.1823	0.2236	0.3682	0.4468	0.5077	0.5611	0.4301	0.2278
2022	0.5524	0.5576	0.4485	0.8284	0.4776	0.2391	0.5251	0.4995	0.4588	0.4533	0.5508	0.4580	0.4611
2023	0.6278	0.6302	0.4455	0.7590	0.5506	0.9105	0.7603	0.5648	0.4629	0.4477	0.5198	0.5115	0.5838

Table A3
Distance vector and standard deviation vector (for Economic Performance)

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}	C_{12}	C_{13}
D_j	0.2270	0.2286	0.2033	0.2369	0.2041	0.3331	0.2656	0.2135	0.2002	0.2013	0.2002	0.2014	0.2145
σ_j	0.1541	0.1581	0.0566	0.2794	0.0633	0.2827	0.2223	0.1125	0.0124	0.0361	0.0178	0.0369	0.1164

Table A4
The first logarithmic normalization matrix (for Economic Performance)

L_{ij}^{1st}	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}	C_{12}	C_{13}
2019	0.2004	0.1956	0.1882	0.2018	0.1973	0.1912	0.1581	0.2050	0.1988	0.1991	0.2009	0.1970	0.2000
2020	0.1862	0.1832	0.1980	0.1938	0.1979	0.1941	0.1828	0.1828	0.1990	0.1986	0.2006	0.1983	0.2018
2021	0.1959	0.2002	0.2119	0.2011	0.1987	0.1906	0.1740	0.1960	0.2000	0.2019	0.2004	0.1989	0.1925
2022	0.2074	0.2090	0.2011	0.2025	0.2017	0.1968	0.2303	0.2060	0.2009	0.2003	0.1999	0.2010	0.2014
2023	0.2101	0.2120	0.2007	0.2008	0.2044	0.2273	0.2547	0.2101	0.2012	0.2001	0.1983	0.2047	0.2044

Table A5
The second logarithmic normalization matrix (for Economic Performance)

L_{ij}^{2nd}	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}	C_{12}	C_{13}
2019	0.2004	0.1956	0.1882	0.8071	0.1973	0.1912	0.1581	0.2050	0.1988	0.1991	0.8035	0.1970	0.2000
2020	0.1862	0.1832	0.1980	0.7754	0.1979	0.1941	0.1828	0.1828	0.1990	0.1986	0.8022	0.1983	0.2018
2021	0.1959	0.2002	0.2119	0.8042	0.1987	0.1906	0.1740	0.1960	0.2000	0.2019	0.8016	0.1989	0.1925
2022	0.2074	0.2090	0.2011	0.8102	0.2017	0.1968	0.2303	0.2060	0.2009	0.2003	0.7994	0.2010	0.2014
2023	0.2101	0.2120	0.2007	0.8031	0.2044	0.2273	0.2547	0.2101	0.2012	0.2001	0.7933	0.2047	0.2044

Table A6
Aggregated normalized matrix (for Economic Performance)

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}	C_{12}	C_{13}
2019	0.2004	0.1956	0.1882	0.4540	0.1973	0.1912	0.1581	0.2050	0.1988	0.1991	0.4519	0.1970	0.2000
2020	0.1862	0.1832	0.1980	0.4362	0.1979	0.1941	0.1828	0.1828	0.1990	0.1986	0.4513	0.1983	0.2018
2021	0.1959	0.2002	0.2119	0.4524	0.1987	0.1906	0.1740	0.1960	0.2000	0.2019	0.4509	0.1989	0.1925
2022	0.2074	0.2090	0.2011	0.4557	0.2017	0.1968	0.2303	0.2060	0.2009	0.2003	0.4497	0.2010	0.2014
2023	0.2101	0.2120	0.2007	0.4517	0.2044	0.2273	0.2547	0.2101	0.2012	0.2001	0.4462	0.2047	0.2044

Table A7
Weighted aggregated matrix (for Economic Performance)

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}	C_{12}	C_{13}
2019	0.0182	0.0184	0.0056	0.0781	0.0066	0.0468	0.0243	0.0128	0.0013	0.0038	0.0042	0.0038	0.0130
2020	0.0169	0.0172	0.0059	0.0750	0.0066	0.0475	0.0281	0.0114	0.0013	0.0038	0.0042	0.0038	0.0131
2021	0.0178	0.0188	0.0063	0.0778	0.0067	0.0467	0.0267	0.0122	0.0013	0.0038	0.0042	0.0038	0.0125
2022	0.0189	0.0196	0.0060	0.0784	0.0068	0.0482	0.0353	0.0129	0.0013	0.0038	0.0042	0.0039	0.0131
2023	0.0191	0.0199	0.0060	0.0777	0.0069	0.0556	0.0391	0.0131	0.0013	0.0038	0.0041	0.0040	0.0133

Table A8
Total vector of cost-based criteria and total vector of benefit-based criteria (for Economic Performance)

	R_i^-	R_i^+
2019	0.0823	0.1546
2020	0.0792	0.1557
2021	0.0820	0.1567
2022	0.0826	0.1697
2023	0.0819	0.1821

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