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Evaluating The Logistics Performance Index of European Union Countries: An Integrated Multi-Criteria Decision-Making Approach Utilizing the Bonferroni Operator

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Abstract: The evaluation of the Logistics Performance Index (LPI), as computed by the World Bank, incorporates six equally weighted criteria to ascertain the overall performance scores of countries globally. This study aims to scrutinize the impact of the weighting coefficients of criteria on the computation of the total LPI scores, employing a selection of Multi-Criteria Decision Making (MCDM) methods. The Criteria Importance Through Intercriteria Correlation (CRITIC) and Full Consistency Method (FUCOM) methods were utilized to determine the weighting coefficients, while the Measurement of Alternatives and Ranking according to Compromise Solution (MARCOS) method was employed for ranking the European Union member states. The findings reveal that Finland emerges as the top-ranked nation upon application of the integrated MCDM model. A comparative analysis was conducted, incorporating three additional MCDM methods to assess the robustness of the ranking. Furthermore, a sensitivity analysis was performed, generating sixty novel scenarios to examine the effects of variations in the criteria weighting coefficients. This analysis confirmed the influence of these coefficients on the ultimate ranking of the nations. The research underscores the significance of criteria weightings in the evaluation of the LPI and provides insights into the stability of the rankings under different weighting scenarios.

Keywords: Logistics Performance Index (LPI); Criteria Importance Through Intercriteria Correlation (CRITIC) method; Full Consistency Method (FUCOM) method; Measurement of Alternatives and Ranking according to Compromise Solution (MARCOS) method; Criteria weight; Ranking; Comparative analysis; Sensitivity analysis

1 Introduction

Logistics, increasingly recognized as pivotal in shaping global trade relations, is now likened to the economic system's "bloodstream", reflecting its critical linkage with the demand for logistics services and the prevailing economic conditions [1, 2]. This analogy highlights the essentiality of a robust and efficient logistics network, necessitating the continual assessment of logistics performance. Such evaluations are adeptly conducted employing a suite of methods and the integration of MCDM models. In assessing the logistics performance of transitional nations, Ulutaş and Karaköy [3] have synthesized the grey SWARA (Step-wise Weight Assessment Ratio Analysis) and grey MOORA (Multi-objective Optimization on the basis of Ratio Analysis) methods, pinpointing infrastructure as the paramount criterion, with Serbia emerging as the foremost country in this regard. In their analytical exploration, Isik et al. [4] employed the Statistical Variance (SV) and Multi-Attributive Border Approximation area Comparison (MABAC) methods within an integrated MCDM framework to scrutinize and appraise the logistics performance across eleven Central and Eastern European countries. The concordance of the rankings derived from this model with those of the World Bank underscores the model's reliability and validity. To evaluate the logistics performance of OECD counties (The Organization for Economic Cooperation and Development), Çakır [5] innovated by incorporating the CRITIC, Simple Additive Weighting (SAW), and Peters' fuzzy regression method, establishing this integrated approach as a potent alternative for logistics performance assessment of the involved countries. Further, the investigative work by Yildirim and Mercangoz [6] addressed the assessment of LPI scores within the OECD context, applying the fuzzy Analytic Hierarchy Process (AHP) to establish criteria weights, and the ARAS-G method for alternative evaluation. The substantial outcomes of their study affirm the significance of the applied model. Mercangoz et al. [7] tackled the inherent uncertainties within MCDM through the application of grey system theory, amalgamated with MCDM methodologies to develop an integrated grey numbers-COPRAS (Complex Proportional Assessment) model. Their findings suggest that this model serves as an efficacious instrument for evaluating the LPI scores of nations. Complementing this, Yu and Hsiao [8] introduced a Meta-DEA-AR (meta-frontier data envelopment analysis with assurance regions) method, offering a novel perspective for appraising the efficiency of countries' logistics performance indices, with a particular emphasis on varying income levels. The congruence between the rankings yielded by this model and those released by the World Bank lends credence to the model's comparative accuracy.

Ulutaş and Karaköy [9] crafted an innovative model that blends both subjective and objective analysis for the calculation of criteria weighting coefficients by integrating the SWARA and CRITIC methods. Miškić et al. [10] proceeded to assess the LPI of EU countries, implementing an integrated MEREC (Method based on the Removal Effects of Criteria) and MARCOS model. Complementarily, Arikan Kargi [11] utilized the ENTROPY and WASPAS (Weighted Aggregated Sum Product Assessment) methods to scrutinize the 2018 LPI outcomes of OECD countries, concluding that infrastructure emerges as the preeminent criterion with Germany securing the position as the top-performing country.

Mešić et al. [12] adopted an integrated CRITIC-MARCOS model for the appraisal of LPI scores within Western Balkan countries. The sensitivity analysis implemented in their study suggests that alterations in the criteria weighting coefficients do indeed impact the final rankings derived from the MCDM model, albeit marginally, which is attributed to the limited array of alternatives considered. In a parallel vein, Rezaei et al. [13] applied the Best Worst Method (BWM) to ascertain the importance of the sextet of criteria underpinning the computation of the LPI scores. Their conclusions posited that while these weights subtly affect the rankings due to the interrelations among the LPI indicators, they hold substantial potential to influence the establishment of disparate policy priorities in the calculation of LPI values. Çalık et al. [14] conducted a comprehensive study integrating a plethora of MCDM methodologies, including the AHP, Fuzzy AHP (FAHP), Pythagorean Fuzzy AHP (PFAHP), TOPSIS (Technique for Order Preference by Similarity to Ideal Solution), VIKOR (Višekriterijumska Optimizacija i Kompromisno Rješenje), CODAS (Combinative Distance-based Assessment), and the Base Criterion Method (BCM). The research underscores the criticality of precise criterion weight determination, highlighting the substantial influence that varying these weights has on the final evaluative outcomes. Building on this concept, Stević et al. [15] corroborated the profound impact that weighting coefficients of criteria have on the final rankings of alternatives, utilizing an integrated CRITIC-MARCOS model. Their study encompassed an analysis of Balkan countries and introduced 36 novel scenarios within a sensitivity analysis to adjust the criteria weights, with the findings revealing that the magnitude of changes in individual criteria's values significantly sways the ultimate ranking of alternatives.

2 Methodology

The steps of MCDM methods applied in this paper are shown and explained in detail below.

2.1 CRITIC Method

The CRITIC method represents an objective method, which uses a given set of quantitative parameters on the basis of which the weights of the criteria are determined. The CRITIC method is carried out through six steps [16]:

Step 1. Forming an initial matrix (1):

$$X_{ij} = \begin{bmatrix} x_{11} & x_{12} & \dots & x_{1n} \\ x_{21} & x_{22} & \dots & x_{2n} \\ \dots & \dots & \dots & \dots \\ x_{m1} & x_{m2} & \dots & x_{mn} \end{bmatrix} \tag{1}$$

Step 2. Normalization depending on the type of criteria (2) and (3):

$$r_{ij} = \frac{x_{ij} - \min x_{ij}}{\max x_{ij} - \min x_{ij}} \quad \text{if } j \in B \to \max \tag{2}$$

$$r_{ij} = \frac{x_{ij} - \max x_{ij}}{\min x_{ij} - \max x_{ij}} \quad \text{if } j \in C \to \min \tag{3}$$

Step 3. Determination of the symmetric linear correlation matrix (4):

$$r_{ij} = \frac{n\sum x_i y_i - \sum x_i \sum y_i}{\sqrt{n\sum x_i^2 - \left(\sum x_i\right)^2} \cdot \sqrt{n\sum y_i^2 - \left(\sum y_i\right)^2}} \tag{4}$$

Step 4. Calculation of the standard deviation (σ) (5) and the sum of the matrix $1 - r_{ij}$ (6):

$$\sigma = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})^2} \tag{5}$$

$$\sum_{j=1}^{n}(1 - r_{ij}) \tag{6}$$

Step 5. Determination of the amount of information in relation to each criterion by applying Eq. (7):

$$C_j = \sigma \sum_{j=1}^{n} 1 - r_{ij} \tag{7}$$

Step 6. Calculation of criteria weights using Eq. (8):

$$W_j = \frac{C_j}{\sum_{j=1}^{n} C_j} \tag{8}$$

2.2 FUCOM Method

The procedure for obtaining the weighting coefficients of the criteria using FUCOM is as follows [17]:
Step 1. Ranking criteria according to their importance (9):

$$C_{j(1)} > C_{j(2)} > \cdots > C_{j(k)} \tag{9}$$

Step 2. Mutual comparison of ranked criteria and determination of comparative importance of evaluation criteria. The comparative importance of the evaluation criteria $\left(\varphi_{k/(k+1)}\right)$ represents the advantage that the criterion of the rank $C_{j(k)}$ has compared to the criteria of the rank $C_{j(k+l)}(10)$:

$$\phi = \left(\varphi_{1/2}, \varphi_{2/3}, \ldots, \varphi_{k/(k+1)}\right) \tag{10}$$

Step 3. Calculation of the final values of the weighting coefficients of the evaluation criteria $\left(w_1, w_2, \ldots, w_n\right)^{\mathrm{T}}$. Comparative importance between the observed criteria $\left(\varphi_{k/(k+1)}\right)$, which is defined in step 2, i.e., that the following condition is met:

$$\frac{w_k}{w_{k+1}} = \varphi_{k/(k+1)} \tag{11}$$

Another condition that should be met by the values of the weighting coefficients of the criteria is the condition of mathematical transitivity:

$$\frac{w_k}{w_{k+2}} = \varphi_{k/(k+1)} \times \varphi_{(k+1)/(k+2)} \tag{12}$$

Based on the defined settings, the final model can be established for determining the values of the weighting coefficients for the evaluation criteria.

$$\begin{aligned}&\min \chi \\ &\left|\frac{w_{j(k)}}{w_{j(k+1)}} - \varphi_{k/(k+1)}\right| = \chi; \forall j \\ &\left|\frac{w_{j(k)}}{w_{j(k+2)}} - \varphi_{k/(k+1)} \times \varphi_{(k+1)/(k+2)}\right| = \chi; \forall j\end{aligned} \tag{13}$$

$$\sum_{j=1}^{n} w_j = 1 \tag{14}$$

$$w_j \geq 0; \forall j \tag{15}$$

By solving the model (13), we obtain the final values of the evaluation criteria $(w_1, w_2, \ldots, w_n)^{\mathrm{T}}$ and the degree of consistency (χ) of the results obtained.

2.3 MARCOS Method

The MARCOS method is a MCDM method used to rank alternatives. It is carried out through the following steps [18]:

Step 1. Formation of an initial decision matrix.

Step 2. Formation of an extended initial matrix (16):

$$X = \begin{array}{c} \\ AAI \\ A_1 \\ A_2 \\ \ldots \\ A_m \\ AI \end{array} \begin{array}{c} \begin{array}{cccc} C_1 & C_2 & \ldots & C_n \end{array} \\ \begin{bmatrix} x_{aa1} & x_{aa2} & \ldots & x_{aan} \\ x_{11} & x_{12} & \ldots & x_{1n} \\ x_{21} & x_{22} & \ldots & x_{2n} \\ \ldots & \ldots & \ldots & \ldots \\ x_{m1} & x_{m2} & \ldots & x_{mn} \\ x_{ai1} & x_{ai2} & \ldots & x_{ain} \end{bmatrix} \end{array} \tag{16}$$

Step 3. Normalization of the extended initial matrix (X) by applying Eqs. (17) or (18):

$$n_{ij} = \frac{x_{ai}}{x_{ij}}; j \in C \tag{17}$$

$$n_{ij} = \frac{x_{ij}}{x_{ai}}; j \in B \tag{18}$$

Step 4. Determination of the weighted matrix V using the following equation:

$$v_{ij} = n_{ij} \times w_j \tag{19}$$

Step 5. Calculation of the utility degree of alternatives K_i in relation to the anti-ideal (20) and ideal (21) solution:

$$K_i^- = \frac{s_i}{s_{aai}} \tag{20}$$

$$K_i^+ = \frac{s_i}{s_{ai}} \tag{21}$$

Step 6. Determination of the utility function of alternatives $f(Ki)$:

$$f(K_i)=\frac{K_i^{+}+K_i^{-}}{1+\frac{1-f(K_i^{+})}{f(K_i^{+})}+\frac{1-f(K_i^{-})}{f(K_i^{-})}} \tag{22}$$

where, $f\left(K_i^{-}\right)$ represents the utility function in relation to the anti-ideal solution, while $f\left(K_i^{+}\right)$ represents the utility function in relation to the ideal solution determined by applying Eqs. (23) and (24):

$$f\left(K_i^{-}\right)=\frac{K_i^{+}}{K_i^{+}+K_i^{-}} \tag{23}$$

$$f\left(K_i^{+}\right)=\frac{K_i^{-}}{K_i^{+}+K_i^{-}} \tag{24}$$

Step 7. Ranking alternatives according to the obtained utility function values.

3 Evaluation of the LPI of the EU Countries Using MCDM Methods

In this section, the CRITIC method was initially employed to compute the weighting coefficients for six selected criteria, followed by the application of the FUCOM method. Subsequently, the Bonferroni operator was utilized to average the weighting coefficients derived from these methods. These averaged values of the weighting coefficients were then integrated into the MARCOS method to facilitate the ranking of European Union countries according to their LPI scores. The requisite data for these calculations were extracted from the World Bank's report on the LPI results for the year 2023 [19].

3.1 Calculation of Weighting Coefficients of Criteria Using the CRITIC Method

Table 1. Initial decision matrix of the CRITIC method

	Alternatives	C1	C2	C3	C4	C5	C6
A1	Austria	3.7	3.9	3.8	4.0	4.2	4.3
A2	Belgium	3.9	4.1	3.8	4.2	4.0	4.2
A3	Bulgaria	3.1	3.1	3.0	3.3	3.3	3.5
A4	Czech Republic	3.0	3.0	3.4	3.6	3.2	3.7
A5	Denmark	4.1	4.1	3.6	4.1	4.3	4.1
A6	Estonia	3.2	3.5	3.4	3.7	3.8	4.1
A7	Finland	4.0	4.2	4.1	4.2	4.2	4.3
A8	France	3.7	3.8	3.7	3.8	4.0	4.1
A9	Greece	3.2	3.7	3.8	3.8	3.9	3.9
A10	Croatia	3.0	3.0	3.6	3.4	3.4	3.2
A11	Ireland	3.4	3.5	3.6	3.6	3.7	3.7
A12	Italy	3.4	3.8	3.4	3.8	3.9	3.9
A13	Cyprus	2.9	2.8	3.1	3.2	3.4	3.5
A14	Latvia	3.3	3.3	3.2	3.7	3.6	4.0
A15	Lithuania	3.2	3.5	3.4	3.6	3.1	3.6
A16	Luxembourg	3.6	3.6	3.6	3.9	3.5	3.5
A17	Hungary	2.7	3.1	3.4	3.1	3.4	3.6
A18	Malta	3.4	3.7	3.0	3.4	3.4	3.2
A19	Netherlands	3.9	4.2	3.7	4.2	4.2	4.0
A20	Germany	3.9	4.3	3.7	4.2	4.2	4.1
A21	Poland	3.4	3.5	3.3	3.6	3.8	3.9
A22	Portugal	3.2	3.6	3.1	3.6	3.2	3.6
A23	Romania	2.7	2.9	3.4	3.3	3.5	3.6
A24	Slovakia	3.2	3.3	3.0	3.4	3.3	3.5
A25	Slovenia	3.4	3.6	3.4	3.3	3.0	3.3
A26	Spain	3.6	3.8	3.7	3.9	4.1	4.2
A27	Sweden	4.0	4.2	3.4	4.2	4.1	4.2

Further, the values of the weighting coefficients of the criteria for the LPI results for 2023 were calculated using the CRITIC method. The weighting coefficients were determined for the following six criteria: customs (C1), infrastructure (C2), ease of arranging shipments (C3), quality of logistics services (C4), tracking and tracing of consignments (C5), and timeliness (C6). The first step of the CRITIC method implies the formation of an initial decision matrix, which is shown in Table 1.

In the second step, the initial decision matrix is normalized. Since all six criteria are of the benefit type, the values of the normalized matrix shown in Table 2 are obtained by applying Eq. (2).

Table 2. Normalized initial matrix of the CRITIC method

	Alternatives	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**
A1	Austria	0.714	0.733	0.727	0.818	0.923	1.000
A2	Belgium	0.857	0.867	0.727	1.000	0.769	0.909
A3	Bulgaria	0.286	0.200	0.000	0.182	0.231	0.273
A4	Czech Republic	0.214	0.133	0.364	0.455	0.154	0.455
A5	Denmark	1.000	0.867	0.545	0.909	1.000	0.818
A6	Estonia	0.357	0.467	0.364	0.545	0.615	0.818
A7	Finland	0.929	0.933	1.000	1.000	0.923	1.000
A8	France	0.714	0.667	0.636	0.636	0.769	0.818
A9	Greece	0.357	0.600	0.727	0.636	0.692	0.636
A10	Croatia	0.214	0.133	0.545	0.273	0.308	0.000
A11	Irela	.500	0.467	0.545	0.455	0.538	0.455
A12	Italy	0.500	0.667	0.364	0.636	0.692	0.636
A13	Cyprus	0.143	0.000	0.091	0.091	0.308	0.273
A14	Latvia	0.429	0.333	0.182	0.545	0.462	0.727
A15	Lithuania	0.357	0.467	0.364	0.455	0.077	0.364
A16	Luxembour	0.643	0.533	0.545	0.727	0.385	0.273
A17	Hung	0.000	0.200	0.364	0.000	0.308	0.364
A18	Malta	0.500	0.600	0.000	0.273	0.308	0.000
A19	Netherlands	0.857	0.933	0.636	1.000	0.923	0.727
A20	Germany	0.857	1.000	0.636	1.000	0.923	0.818
A21	Poland	0.500	0.467	0.273	0.455	0.615	0.636
A22	Portugal	0.357	0.533	0.091	0.455	0.154	0.364
A23	Romania	0.000	0.067	0.364	0.182	0.385	0.364
A24	Slovakia	0.357	0.333	0.000	0.273	0.231	0.273
A25	Slovenia	0.500	0.533	0.364	0.182	0.000	0.091
A26	Spain	0.643	0.667	0.636	0.727	0.846	0.909
A27	Sweden	0.929	0.933	0.364	1.000	0.846	0.909

The third step involves determining the symmetric linear correlation matrix using Eq. (4). The values of the linear correlation matrix are shown in Table 3.

Table 3. Symmetric linear correlation matrix

	C1	**C2**	**C3**	**C4**	**C5**	**C6**
C1	1.000	0.931	0.557	0.896	0.757	0.662
C2	0.931	1.000	0.580	0.884	0.754	0.672
C3	0.557	0.580	1.000	0.685	0.681	0.619
C4	0.896	0.884	0.685	1.000	0.827	0.806
C5	0.757	0.754	0.681	0.827	1.000	0.861
C6	0.662	0.672	0.619	0.806	0.861	1.000

In the fourth step, the calculation of the standard deviation (σ) is performed using Eq. (5), as well as the calculation of the sum of the 1- r_{ij} matrix using Eq. (6). The values obtained are shown in Table 4.

The fifth step of the CRITIC method involves determining the amount of information in relation to each criterion (Cj) using Eq. (7). The values of Cj are shown in Table 5.

In the last, sixth step of the CRITIC method, the values of the weighting coefficients of the criteria are determined using Eq. (8). The calculated weighting coefficients of the criteria are shown in Table 6.

Table 4. Values of the $1 - r_{ij}$ matrix and standard deviations

	C1	C2	C3	C4	C5	C6
C1	0.000	0.069	0.443	0.104	0.243	0.338
C2	0.069	0.000	0.420	0.116	0.246	0.328
C3	0.443	0.420	0.000	0.315	0.319	0.381
C4	0.104	0.116	0.315	0.000	0.173	0.194
C5	0.243	0.246	0.319	0.173	0.000	0.139
C6	0.338	0.328	0.381	0.194	0.139	0.000
Σ	1.197	1.179	1.878	0.902	1.120	1.380
STDEV	0.283	0.289	0.257	0.310	0.305	0.307

Table 5. The values of Cj

	C1	C2	C3	C4	C5	C6	ΣCj
Cj	0.338	0.340	0.483	0.279	0.341	0.423	2.204

Table 6. Weighting coefficients of the criteria - Wj

	C1	C2	C3	v C4	C5	C6
Wj	0.153	0.154	0.219	0.127	0.155	0.192

Based on the results from Table 6, it is evident that criterion C3 (ease of arranging shipments) has the highest value of the weighting coefficient, which implies that this criterion is the most important of the six criteria. In second place in terms of importance is criterion C6 (delivery of shipments within scheduled time, i.e., timeliness), followed by criteria C5 (tracking and tracing of consignments), C2 (infrastructure), and criterion C1 (customs). Criterion C4 (quality of logistics services) has the lowest value of the weighting coefficient and represents the criterion of least importance.

3.2 Calculation of the Weighting Coefficients of the Criteria Using the FUCOM Method

In the first step of the FUCOM method, it is necessary to determine the ranking of criteria. The criteria are ranked as follows: $C3 > C5 > C6 > C4 > C1 > C2$; which implies that ease of arranging shipments is presented as the first-ranked criterion, that is, the most important criterion, followed by tracking and tracing of consignments and timeliness, and then the quality of logistics services and customs. The least important criterion is infrastructure.

In the second step, a mutual comparison of the criteria ranked in the first step is performed. The comparison is made in relation to the first-ranked criterion based on the scale [1,5]. In this way, the significance of the criteria is obtained (Table 7).

Table 7. Significance of the criteria

	C1	C2	C3	C4	C5	C6
$\boldsymbol{w_{C_{j(k)}}}$	1	1.15	1.25	1.50	1.70	1.85

After determining the significance of the criteria, the comparative significance of the criteria is calculated $(\varphi_{k/(k+1)})$:

$$\varphi_{C_3/C_5} = 1.15/1.0 = 1.15; \varphi_{C_5/C_6} = 1.25/1.15 = 1.09; \quad \varphi_{C_6/C_4} = 1.50/1.25 = 1.20$$
$$\varphi_{C_4/C_1} = 1.70/1.50 = 1.13; \varphi_{C_1/C_2} = 1.85/1.70 = 1.09$$

The first condition for the final values of the weighting coefficients is adherence to the condition delineated by Eq. (11). The application of this equation yields the following values:

$$W_3/W_5 = 1.15; \quad W_5/W_6 = 1.09; \quad W_6/W_4 = 1.20; \quad W_4/W_1 = 1.13; \quad W_1/W_2 = 1.09$$

Another condition that should be fulfilled by the final values of the weighting coefficients is the condition of mathematical transitivity, defined by Eq. (12). Fulfilling the previously defined condition, the following values are obtained:

$$\frac{W_3}{W_6} = \varphi_{C_3/C_5} \times \varphi_{C_5/C_6} = 1.15 \times 1.09 = 1.25$$
$$\frac{W_5}{W_4} = \varphi_{C_5/C_6} \times \varphi_{C_6/C_4} = 1.09 \times 1.20 = 1.31$$
$$\frac{W_6}{W_1} = \varphi_{C_6/C_4} \times \varphi_{C_4/C_1} = 1.20 \times 1.13 = 1.36$$
$$\frac{W_4}{W_2} = \varphi_{C_4/C_1} \times \varphi_{C_1/C_2} = 1.13 \times 1.09 = 1.23$$

The final model for determining the weighting coefficients of the criteria is defined by applying Eq. (13) and is as follows:

$$\min \chi$$
$$\left|\frac{W_3}{W_5} - 1.15\right| \le \chi; \left|\frac{W_5}{W_6} - 1.09\right| \le \chi; ||\frac{W_6}{W_4} - 1.20| \le \chi; |\frac{W_4}{W_1} - 1.13| \le \chi; |\frac{W_1}{W_2} - 1.09| \le \chi; |\frac{W_3}{W_6} - 1.25 | \le \chi;$$
$$\left|\frac{W_5}{W_4} - 1.31\right| \le \chi; \left|\frac{W_6}{W_1} - 1.36\right| \le \chi; \left|\frac{W_4}{W_2} - 1.23\right| \le \chi$$

By solving this model, the values of the weighting coefficients, shown in Table 8, are obtained.

Table 8. Values of wj obtained using the FUCOM method

	C1	C2	C3	C4	C5	C6	χ
$\boldsymbol{Wj}$	0.132	0.121	0.224	0.149	0.195	0.179	0.000

The analysis of the results reveals that the criterion of ease of arranging shipments (C3) holds the greatest significance, with a weighting coefficient of 0.224. This is followed by the tracking and tracing of consignments (C5) as the second most critical criterion, assigned a weighting coefficient of 0.195. The criterion of timeliness (C6) comes next with a coefficient of 0.179, preceded by the quality of logistics services (C4) with a coefficient of 0.149. Ranked lower in importance are the customs criterion (C1) with a coefficient of 0.132, and infrastructure (C2), which is deemed the least significant with the lowest weighting coefficient of 0.121 amongst the criteria evaluated. The deviation from complete consistency is indicated by $\chi = 0.000$, signifying that the results have achieved full consistency.

3.3 Averaging the Values of Weighting Coefficients of the Criteria – Bonferroni Operator

After calculating the values of the weighting coefficients of the criteria using the CRITIC method (Table 6), and then using the FUCOM method (Table 8), it is necessary to average the values of the weighting coefficients of the criteria using the Bonferroni operator [20] according to the following equation:

$$a_j = \left(\frac{1}{e(e-1)} \sum_{\substack{i,j=1 \\ i \neq j}}^{e} a_i^p \times a_j^q \right)^{\frac{1}{p+q}} \tag{25}$$

The final values of the weighting coefficients of the criteria are given in Table 9.

Table 9. The final values of the weighting coefficients of the criteria

	C1	C2	C3	C4	C5	C6
$\boldsymbol{Wj}$	0.142	0.137	0.221	0.138	0.174	0.185

3.4 Ranking of EU Countries Based on LPI 2023 Results Using the MARCOS Method

Based on the LPI 2023 results, the ranking of 27 EU countries was carried out using the MARCOS method. The first step involves forming an initial decision matrix (the same as the initial matrix formed in Table 1). In the second step, an extended initial decision matrix with defined ideal (AI) and anti-ideal (AAI) solutions is formed. The extended initial decision matrix of the MARCOS method is shown in Table 10.

Table 10. Extended initial decision matrix of the MARCOS method

Alternatives	C1	C2	C3	C4	C5	C6
AAI	**2.7**	**2.8**	**3.0**	**3.1**	**3.0**	**3.2**
Al	3.7	3.9	3.8	4.0	4.2	4.3
A2	3.9	4.1	3.8	4.2	4.0	4.2
A3	3.1	3.1	3.0	3.3	3.3	3.5
A4	3.0	3.0	3.4	3.6	3.2	3.7
A5	4.1	4.1	3.6	4.1	4.3	4.1
A6	3.2	3.5	3.4	3.7	3.8	4.1
A7	4.0	4.2	4.1	4.2	4.2	4.3
A8	3.7	3.8	3.7	3.8	4.0	4.1
A9	3.2	3.7	3.8	3.8	3.9	3.9
A10	3.0	3.0	3.6	3.4	3.4	3.2
Al1	3.4	3.5	3.6	3.6	3.7	3.7
A12	3.4	3.8	3.4	3.8	3.9	3.9
A13	2.9	2.8	3.1	3.2	3.4	3.5
Al4	3.3	3.3	3.2	3.7	3.6	4.0
A15	3.2	3.5	3.4	3.6	3.1	3.6
A16	3.6	3.6	3.6	3.9	3.5	3.5
A17	2.7	3.1	3.4	3.1	3.4	3.6
A18	3.4	3.7	3.0	3.4	3.4	3.2
A19	3.9	4.2	3.7	4.2	4.2	4.0
A20	3.9	4.3	3.7	4.2	4.2	4.1
A21	3.4	3.5	3.3	3.6	3.8	3.9
A22	3.2	3.6	3.1	3.6	3.2	3.6
A23	2.7	2.9	3.4	3.3	3.5	3.6
A24	3.2	3.3	3.0	3.4	3.3	3.5
A25	3.4	3.6	3.4	3.3	3.0	3.3
A26	3.6	3.8	3.7	3.9	4.1	4.2
A27	4.0	4.2	3.4	4.2	4.1	4.2
AI	**4.1**	**4.3**	**4.1**	**4.2**	**4.3**	**4.3**

Table 11. Normalized extended matrix of the MARCOS method

Alternatives	C1	C2	C3	C4	C5	C6
AAI	0.659	0.651	0.732	0.738	0.698	0.744
A1	0.902	0.907	0.927	0.952	0.977	1.000
A2	0.951	0.953	0.927	1.000	0.930	0.977
A3	0.756	0.721	0.732	0.786	0.767	0.814
A4	0.732	0.698	0.829	0.857	0.744	0.860
A5	1.000	0.953	0.878	0.976	1.000	0.953
A6	0.780	0.814	0.829	0.881	0.884	0.953
A7	0.976	0.977	1.000	1.000	0.977	1.000
A8	0.902	0.884	0.902	0.905	0.930	0.953
A9	0.780	0.860	0.927	0.905	0.907	0.907
A10	0.732	0.698	0.878	0.810	0.791	0.744
A11	0.829	0.814	0.878	0.857	0.860	0.860
A12	0.829	0.884	0.829	0.905	0.907	0.907
A13	0.707	0.651	0.756	0.762	0.791	0.814
A14	0.805	0.767	0.780	0.881	0.837	0.930
A15	0.780	0.814	0.829	0.857	0.721	0.837
A16	0.878	0.837	0.878	0.929	0.814	0.814
A17	0.659	0.721	0.829	0.738	0.791	0.837
A18	0.829	0.860	0.732	0.810	0.791	0.744
A19	0.951	0.977	0.902	1.000	0.977	0.930
A20	0.951	1.000	0.902	1.000	0.977	0.953
A21	0.829	0.814	0.805	0.857	0.884	0.907
A22	0.780	0.837	0.756	0.857	0.744	0.837
A23	0.659	0.674	0.829	0.786	0.814	0.837
A24	0.780	0.767	0.732	0.810	0.767	0.814
A25	0.829	0.837	0.829	0.786	0.698	0.767
A26	0.878	0.884	0.902	0.929	0.953	0.977
A27	0.976	0.977	0.829	1.000	0.953	0.977
AI	1.000	1.000	1.000	1.000	1.000	1.000

The third step of the MARCOS method involves the normalization of the extended initial decision matrix. Since all six criteria are of the benefit type, the elements of the normalized extended decision matrix are obtained by applying Eq. (18), and the obtained values are shown in Table 11.

Table 12. Weighted normalized decision matrix of the MARCOS method

Alternatives	C1	C2	C3	C4	C5	C6
AAI	0.094	0.089	0.162	0.102	0.121	0.138
Al	0.128	0.124	0.205	0.131	0.170	0.185
A2	0.135	0.130	0.205	0.138	0.162	0.181
A3	0.108	0.099	0.162	0.108	0.133	0.151
A4	0.104	0.095	0.184	0.118	0.129	0.160
A5	0.142	0.130	0.194	0.134	0.174	0.177
A6	0.111	0.111	0.184	0.121	0.153	0.177
A7	0.139	0.133	0.221	0.138	0.170	0.185
A8	0.128	0.121	0.200	0.124	0.162	0.177
A9	0.111	0.118	0.205	0.124	0.157	0.168
A10	0.104	0.095	0.194	0.111	0.137	0.138
All	0.118	0.111	0.194	0.118	0.149	0.160
A12	0.118	0.121	0.184	0.124	0.157	0.168
A13	0.101	0.089	0.167	0.105	0.137	0.151
A14	0.114	0.105	0.173	0.121	0.145	0.172
A15	0.111	0.111	0.184	0.118	0.125	0.155
A16	0.125	0.114	0.194	0.128	0.141	0.151
A17	0.094	0.099	0.184	0.102	0.137	0.155
A18	0.118	0.118	0.162	0.111	0.137	0.138
A19	0.135	0.133	0.200	0.138	0.170	0.172
A20	0.135	0.137	0.200	0.138	0.170	0.177
A21	0.118	0.111	0.178	0.118	0.153	0.168
A22	0.111	0.114	0.167	0.118	0.129	0.155
A23	0.094	0.092	0.184	0.108	0.141	0.155
A24	0.111	0.105	0.162	0.111	0.133	0.151
A25	0.118	0.114	0.184	0.108	0.121	0.142
A26	0.125	0.121	0.200	0.128	0.166	0.181
A27	0.139	0.133	0.184	0.138	0.166	0.181
AI	0.142	0.137	0.221	0.138	0.174	0.185

Table 13. Ranking results using the MARCOS method

Alternatives	Si	Ki-	Ki+	fK-	fK+	fKi	RANK
AAI	0.705	1.000					
A1	0.943	1.338	0.946	0.414	0.586	0.732	6
A2	0.951	1.348	0.954	0.414	0.586	0.738	4
A3	0.760	1.078	0.763	0.414	0.586	0.590	26
A4	0.790	1.120	0.792	0.414	0.586	0.613	19
A5	0.952	1.349	0.955	0.414	0.586	0.738	3
A6	0.857	1.215	0.860	0.414	0.586	0.665	12
A7	0.986	1.398	0.989	0.414	0.586	0.765	1
A8	0.912	1.293	0.915	0.414	0.586	0.707	9
A9	0.884	1.253	0.887	0.414	0.586	0.686	10
A10	0.780	1.107	0.783	0.414	0.586	0.605	22
A11	0.850	1.206	0.853	0.414	0.586	0.660	14
A12	0.872	1.237	0.875	0.414	0.586	0.677	11
A13	0.750	1.063	0.752	0.414	0.586	0.582	27
A14	0.831	1.178	0.834	0.414	0.586	0.645	16
A15	0.804	1.140	0.807	0.414	0.586	0.624	17
A16	0.854	1.210	0.856	0.414	0.586	0.662	13
A17	0.770	1.092	0.772	0.414	0.586	0.597	25
A18	0.784	1.112	0.787	0.414	0.586	0.608	21
A19	0.948	1.344	0.951	0.414	0.586	0.736	5
A20	0.956	1.355	0.959	0.414	0.586	0.741	2
A21	0.847	1.201	0.850	0.414	0.586	0.657	15
A22	0.795	1.127	0.798	0.414	0.586	0.617	18
A23	0.774	1.098	0.776	0.414	0.586	0.600	23
A24	0.773	1.097	0.776	0.414	0.586	0.600	24
A25	0.787	1.117	0.790	0.414	0.586	0.611	20
A26	0.920	1.304	0.923	0.414	0.586	0.714	8
A27	0.940	1.333	0.943	0.414	0.586	0.729	7
AI	0.997		1.000				

In the fourth step, it is necessary to form a weighted normalized matrix by applying Eq. (19). The values of Wj are taken from Table 9, and the values of the weighted normalized matrix are shown in Table 12.

Further, the utility degree of alternatives Ki is calculated in relation to the ideal and anti-ideal solution using Eqs. (20) and (21), and the obtained values are shown in Table 13. After calculating the values of the utility degree of the alternatives, the utility function of the alternatives is calculated in relation to the ideal and anti-ideal solution by applying Eq. (23), and Eq. (24). The obtained values are found in Table 13. The final values of the utility function of the alternatives f(Ki) are obtained by applying Eq. (22). The values obtained in this way are also shown in Table 13. In the last step, the alternatives are ranked based on the previously calculated values of the utility functions. The final ranking of the alternatives obtained by applying the MARCOS method is shown in Table 13.

The table above indicates that Finland is the top-ranked EU countries. Following Finland, Germany holds the second position, succeeded by Denmark, Belgium, and the Netherlands. The upper echelon also includes Austria at rank 6, Sweden at rank 7, Spain at rank 8, France at rank 9, and Greece rounding out the top ten. The subsequent rankings for EU countries are as follows: Italy at rank 11, Estonia at rank 12, Luxembourg at rank 13, Ireland at rank 14, Poland at rank 15, Latvia at rank 16, Lithuania at rank 17, Portugal at rank 18, the Czech Republic at rank 19, and Slovenia at rank 20. Malta occupies rank 21, followed by Croatia at rank 22, Romania at rank 23, and Slovakia at rank 24. The lower rankings are held by Hungary at rank 25 and Bulgaria at rank 26, with Cyprus positioned at the bottom of the list at rank 27 within the EU countries.

4 Comparative Analysis and Sensitivity Analysis

For the results obtained by applying a MCDM model in the previous section, a comparative analysis and a sensitivity analysis are performed in this section.

4.1 Comparative Analysis of Results

Comparative analysis involves comparing the results of the ranking of alternatives using the MARCOS method with the results of ranking using other MCDM methods - the WASPAS, EDAS and ARAS methods. Table 14 shows the results of the comparative analysis.

Table 14. Ranking results obtained by applying MCDM methods

	MARCOS		**WASPAS**		**EDAS**		**ARAS**	
Alternatives	fKi	**Rank**	Ai	**Rank**	ASi	**Rank**	Ki	**Rank**
A1	0.732	**6**	0.945	**6**	0.836	**6**	0.946	**6**
A2	0.738	**4**	0.952	**4**	0.865	**4**	0.954	**4**
A3	0.590	**26**	0.761	**26**	0.050	**26**	0.762	**26**
A4	0.613	**19**	0.790	**19**	0.188	**19**	0.791	**19**
A5	0.738	**3**	0.953	**3**	0.869	**3**	0.954	**3**
A6	0.665	**12**	0.858	**12**	0.493	**12**	0.859	**12**
A7	0.765	**1**	0.988	**1**	1.000	**1**	0.989	**1**
A8	0.707	**9**	0.913	**9**	0.717	**9**	0.914	**9**
A9	0.686	**10**	0.885	**10**	0.603	**10**	0.886	**10**
A10	0.605	**22**	0.781	**22**	0.141	**22**	0.783	**22**
A11	0.660	**14**	0.852	**14**	0.474	**14**	0.853	**14**
A12	0.677	**11**	0.874	**11**	0.564	**11**	0.875	**11**
A13	0.582	**27**	0.751	**27**	0.000	**27**	0.751	**27**
A14	0.645	**16**	0.832	**16**	0.377	**16**	0.833	**16**
A15	0.624	**17**	0.805	**17**	0.261	**17**	0.806	**17**
A16	0.662	**13**	0.855	**13**	0.478	**13**	0.856	**13**
A17	0.597	**25**	0.770	**25**	0.096	**25**	0.772	**25**
A18	0.608	**21**	0.785	**21**	0.166	**21**	0.787	**21**
A19	0.736	**5**	0.949	**5**	0.856	**5**	0.951	**5**
A20	0.741	**2**	0.957	**2**	0.884	**2**	0.958	**2**
A21	0.657	**15**	0.848	**15**	0.454	**15**	0.849	**15**
A22	0.617	**18**	0.796	**18**	0.217	**18**	0.797	**18**
A23	0.600	**23**	0.774	**24**	0.115	**23**	0.775	**23**
A24	0.600	**24**	0.775	**23**	0.113	**24**	0.775	**24**
A25	0.611	**20**	0.788	**20**	0.186	**20**	0.791	**20**
A26	0.714	**8**	0.921	**8**	0.746	**8**	0.922	**8**
A27	0.729	**7**	0.940	**7**	0.820	**7**	0.942	**7**

The ranking presented in the table reveals that Finland (A7) consistently emerges as the leading alternative across the MARCOS, EDAS, and ARAS methods, signifying its status as the EU country with the most commendable logistics performance. Subsequent positions are occupied by Germany (A20) at second, Denmark (A5) at third, Belgium (A2) at fourth, and the Netherlands (A19) at fifth. The top ten is completed by Austria (A1), Sweden (A27), Spain (A26), France (A8), and Greece (A9). The ranks proceeding from 11 to 27, as determined by the MARCOS, EDAS, and ARAS methods, are consecutively held by Italy (A12), Estonia (A6), Luxembourg (A16), Ireland (A11), Poland (A21), Latvia (A14), Lithuania (A15), Portugal (A22), the Czech Republic (A4), Slovenia (A25), Malta (A18), Croatia (A10), Romania (A23), Slovakia (A24), Hungary (A17), Bulgaria (A3), with Cyprus (A13) anchoring the list as the lowest-ranked EU country. Notably, the WASPAS method deviates slightly in the ranking of alternatives 23 and 24, where Romania (A23) and Slovakia (A24) exchange places, assigning Slovakia to rank 23 and Romania to rank 24. The positions of all other alternatives remain unchanged in the overall ranking.

In order to determine the correlation of the ranks obtained using the WASPAS, EDAS and ARAS methods with the initial rank obtained using the MARCOS method, the Spearman correlation coefficient (SCC) coefficient [21] is calculated using the following equation:

$$r_s = 1 - \frac{6\sum {d_i}^2}{n\left(n^2-1\right)} \tag{26}$$

In order to have a more detailed insight into the ranking similarity, the Weighted Spearman (WS) coefficient [22] is also calculated, using the following equation:

$$WS = 1 - \sum_{i=1}^{n}\left(2^{-R_{xi}} \cdot \frac{\left|R_{xi}-R_{yi}\right|}{\max\left\{\left|1-R_{xi}\right|, \left|N-R_{xi}\right|\right\}}\right) \tag{27}$$

Figure 1 shows a graphical representation of the correlation of the ranks obtained using the MARCOS WASPAS, EDAS and ARAS methods, that is, the statistical correlation values - SCC coefficient and WS coefficient values.

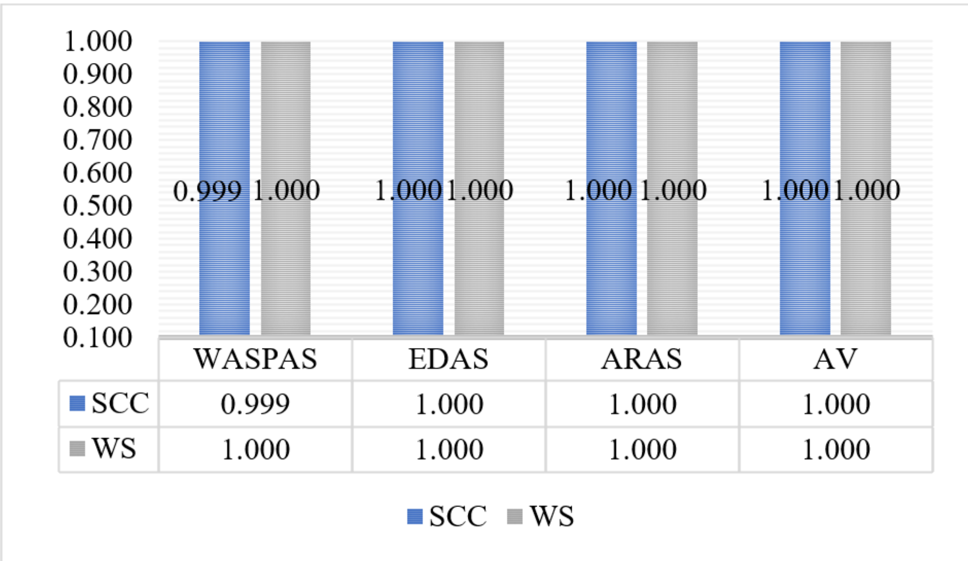

Figure 1. Correlation of ranks

Based on the values obtained using Eq. (26), it can be seen that the MARCOS method has a complete correlation with the EDAS and ARAS methods (SCC=1.00), while the MARCOS and WASPAS method correlation is extremely high (SCC=0.99). A high correlation between the ranks is also shown by the average value of the SCC coefficient (AV), which is SCC=1.00. The results obtained using Eq. (27), that is, the obtained values of the WS coefficient also indicate a complete correlation between the ranks of alternatives obtained applying the MARCOS method and other MCDM methods used in the comparative analysis (SCC=1.00).

4.2 Sensitivity Analysis

The sensitivity analysis implies the creation of 60 new scenarios related to changes in the weight values of all six observed criteria. The values of the weighting coefficients of the criteria were changed in the range of 5-95%, in the following way: the values of criterion C1 changed in scenarios S1-S10, the values of criterion C2 changed in scenarios S11-S20, the values of weighting coefficients of criterion C3 changed in scenarios S21-S30, scenarios S31-S40 implied a change in criterion C4, scenarios S41-S50 a change in criterion C5, while the values of weighting coefficients of criterion C6 changed in the last set of scenarios S51-S60. The scenarios are formed by applying the following Eq. (28) [23]:

$$W_{n\beta} = (1 - W_{n\alpha}) \frac{W_\beta}{(1 - W_n)} \tag{28}$$

The impact of the percentage reduction in the values of the weighting coefficients on the changes in ranks is shown in Figure 2.

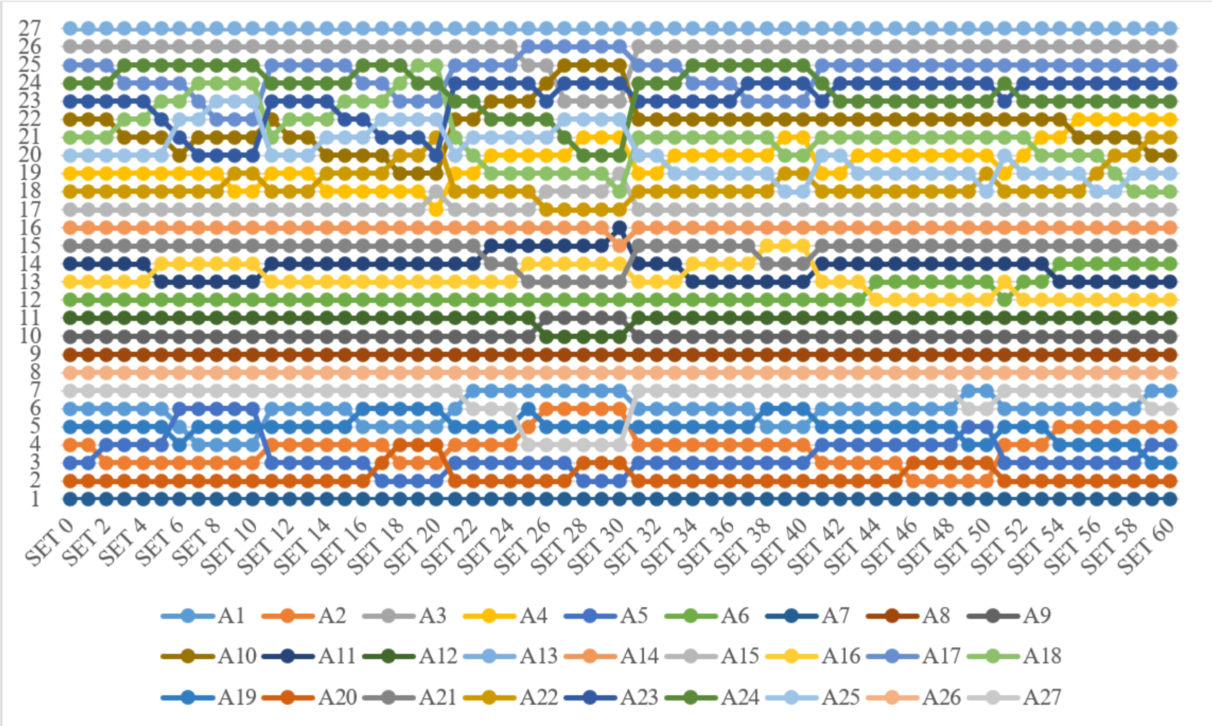

Figure 2. Results of sensitivity analysis for 60 newly formed scenarios

The analysis of results depicted in Figure 2 substantiates that variations in the weighting coefficients of the criteria exert a pronounced influence on the ultimate ranking outcomes. Observations disclose that both the highest-ranked (A7) and the lowest-ranked alternatives (A13) maintain their initial positions consistently across all 60 newly created scenarios. Alongside these, alternatives A26 (rank 8) and A8 (rank 9) also preserve their original rankings irrespective of fluctuations in the criteria weights. Conversely, the remaining alternatives exhibit positional shifts in certain scenarios, contingent upon the weighting coefficients' values. Notably, alternative A14 experiences a minor elevation in rank, ascending from 16th to 15th in scenario S30, where criterion C3's value is reduced by 95%. Similarly, alternatives A9 and A12 interchange their 10th and 11th ranks during scenarios S26-S30, corresponding with a 45-95% decrement in criterion C3's value.

Conversely, scenarios S59 and S60, characterized by an 85% and 95% reduction in criterion C6's value, respectively, catalyze substantial ranking deviations. Here, alternative A4 descends from its original 19th position to 22nd, while significant rank alterations are also evident for alternatives A18 and A22. Alternative A18 ascends from 21st to 18th, and A22 drops from 18th to 21st. Additionally, alternatives A6, A10, and A19 shift by two ranks—A6 slipping from 12th to 14th, A10 climbing from 22nd to 20th, and A19 advancing from 5th to 3rd.

Meanwhile, alternatives A5, A11, A16, A23, A24, A25, and A27, originally ranked 3rd, 14th, 13th, 23rd, 24th, 20th, and 7th, respectively, adjust by a single rank in scenarios S59 and S60 to positions 4th, 13th, 12th, 24th, 23rd, 19th, and 6th, respectively. Moreover, a marked rank decline for alternative A18 occurs in scenario S20 (a 95% decrease in criterion C2), plummeting from the 21st to 25th place, and in scenario S30, A18 ascends from 21st to 18th.

In essence, the findings imply that alterations in the weighting coefficients of all six criteria influence the ranking of alternatives, with criteria C2, C3, and C6 yielding the most significant impact.

Figure 3 shows a graphical representation of the SCC and WS coefficient values for 60 newly formed scenarios.

Figure 3 delineates that the SCC values achieved complete congruence with the preliminary solution in the majority of scenarios (S1-S5; S11-S16; S21-S24; S31-S38; S41-S48; S51-S54). An exceptionally high correlation

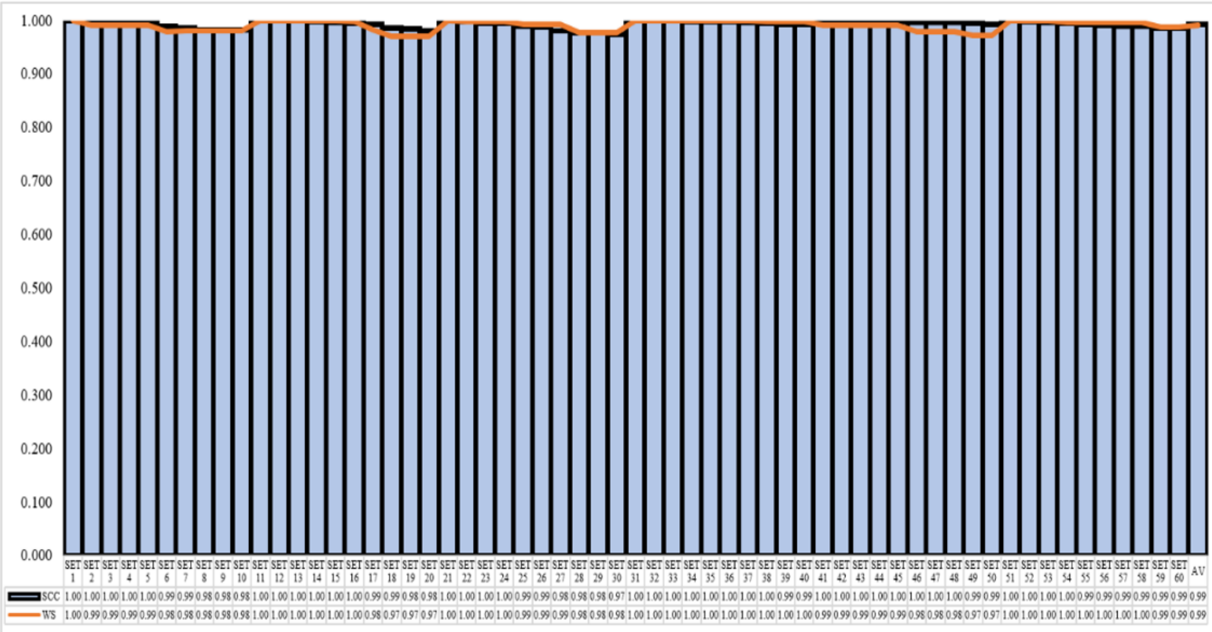

Figure 3. SCC and WS values for 60 newly formed scenarios

was realized in the remaining scenarios: SCC equaled 0.99 in scenarios S6, S7, S17, S18, S25, S26, S39, S40, S49, S50, and S55-S60; SCC stood at 0.98 in scenarios S8-S10, S19, S20, S27-S29; the minimal SCC value was recorded in scenario S30, registering at 0.97. Consequently, the average SCC across all scenarios is notably high, quantifying at 0.99, which denotes a substantial correlation between the ranks. Concurrently, the WS coefficient values indicate complete correlation with the initial solution in numerous scenarios (S1; S11-S16; S21-S24; S31-S40; S51-S58), and a very high correlation, fluctuating between 0.97 to 0.99, in the rest. The average WS coefficient value mirrors that of the SCC, standing at 0.99.

5 Conclusion

The evaluation of EU countries using the 2023 LPI was conducted through an integrated MCDM model. This model encapsulates the integration of both subjective and objective methods—FUCOM and CRITIC, respectively—for the derivation of criteria weighting coefficients, further utilizing the MARCOS method for alternative ranking. Application of these methods yielded averaged values via the Bonferroni operator. The analysis determined criterion C3 as the most pivotal, with C6 following closely. Criteria C5 and C1 were also deemed significant, whereas C4 and C2 were considered of lesser importance. Utilizing the MARCOS method for the ranking of alternatives positioned Finland (A7) as the highest-ranked country, with Cyprus (A13) at the opposite end of the spectrum. Comparative analysis, incorporating the WASPAS, EDAS, and ARAS methods, revealed minimal discrepancies in the final rankings compared to those acquired through the MARCOS method, substantiated by elevated SCC and WS values. Sensitivity analysis, however, indicated that the weighting coefficients of criteria do impact the final evaluative outcomes, with the alternative rankings in sixty newly developed scenarios displaying varying degrees of divergence from the initial criteria set and resultant rankings. This underscores the influence of individual criteria weighting on the robustness and dynamism of the ranking process within the LPI evaluation framework. The consistency in the use of professional terms has been maintained, ensuring terminological precision throughout the analysis. No professional errors were detected within the section provided. The conclusion effectively synthesizes the findings, reflecting the methodological rigor and analytical depth characteristic of high-caliber academic discourse.

Data Availability

The data supporting our research results are included within the article or supplementary material.

Conflicts of Interest

The authors declare no conflict of interest.

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