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Evaluating the Knowledge Economies within the European Union: A Global Knowledge Index Ranking via Entropy and CRADIS Methodologies

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Abstract: In this study, a novel methodology is proposed for ranking the knowledge economies of European Union (EU) countries, leveraging their positioning within the global knowledge index (GKI). The GKI, encompassing seven pivotal indicators, serves as a benchmark for assessing a nation's knowledge economy. The EU, a prominent political and economic conglomerate, forms the focal point of this analysis. A multi-criteria analysis approach is adopted, wherein the Entropy method is utilized to determine the significance of individual GKI indicators. Additionally, the CRADIS (Compromise Ranking of Alternatives from Distance to Ideal Solution) method is employed for the ranking of these nations. The Entropy method, renowned for its efficacy in subjective weight determination, and the CRADIS method, a novel multi-criteria analysis tool yielding results based on deviations from the ideal and anti-ideal solutions, are integrated. This integration is pivotal, as it offers results comparable with other multi-criteria methodologies. The analysis reveals that Research Development and Innovation emerges as the most critical indicator. According to the CRADIS method, Sweden is identified as the leading country in terms of GKI indicators, followed by Finland and Denmark. This trend underscores a superior performance of the northern EU countries. Conversely, Eastern EU countries are observed to lag in their GKI standings. These findings are corroborated through comparative and sensitivity analyses, highlighting the influence of normalization on country rankings and pinpointing specific indicators necessitating enhancement for bolstering the knowledge economy. This research not only aids EU countries in identifying their strengths and weaknesses in the realm of knowledge economy but also serves as a strategic guide for policymakers. It provides actionable insights for fostering knowledge economy development, emphasizing the need for strengthening existing advantages and addressing shortcomings. Such strategic initiatives are crucial for enhancing global market competitiveness. The study's outcomes, therefore, offer valuable resources for decision-making in policy and economic development contexts.

Keywords: Global knowledge index; Knowledge economy; European Union; Multi-criteria analysis; European Union knowledge ranking; Entropy; Compromise ranking of alternatives from distance to ideal solution

1 Introduction

In the contemporary global landscape, knowledge is increasingly recognized as a vital resource for fostering sustainable development, enhancing competitiveness, and driving innovation. The concept of the knowledge economy has emerged as a significant paradigm, shaping new dynamics in scientific collaboration both within the EU and globally [1]. The EU, distinguished by its political and economic stature, is actively engaged in promoting advancement across various sectors among its member states. In this context, the GKI is identified as a critical instrument. It offers an objective, comprehensive assessment of a country's ability to create, disseminate, and utilize knowledge effectively. The GKI is acknowledged as the principal international metric for evaluating the knowledge economy, contributing significantly to the developmental trajectories of countries [2].

It is recognized that the knowledge economy acts as a catalyst for competitiveness and constitutes a fundamental aspect of balanced development within the EU. Investment in innovation and technology is deemed essential for all member states [3]. Moreover, the promotion of a knowledge-based economy is advocated, emphasizing the enhancement of creativity through educational reforms [4]. Various theoretical frameworks have been developed, delineating the pathways for the development of European countries. Among these, sustainable development and the knowledge economy are highlighted as key directions for the EU's progression [5]. The knowledge economy, in particular, is posited as a transformative mechanism for sustainable economic development within the EU member states [6]. The Europe 2020 strategy of the EU articulates a developmental agenda centered on sustainable growth, positioning the knowledge economy as an instrumental means to achieve these objectives [5].

The GKI encompasses a comprehensive spectrum of indicators that span various dimensions of knowledge, including education, innovation, information and communication technologies, and research and development. These multifaceted parameters enable a thorough understanding, not merely of the quantitative facets but also of the qualitative and efficiency aspects of knowledge production and utilization within nations. The GKI is designed to assess the informational efficacy of countries, a measure intrinsically linked to both the knowledge economy and the information society [7]. An analysis of EU countries using the GKI provides critical insights into their respective strengths and weaknesses within the knowledge domain, thereby laying the groundwork for the development of strategies and policies aimed at enhancing their competitive edge in the global marketplace.

This study focuses on the application of the GKI for ranking EU nations, employing multi-criteria analysis methods, notably the entropy and CRADIS methods. The Entropy method, categorized under objective criteria weight determination methods, is utilized in this research to determine the significance of the indicators within the GKI. Conversely, the CRADIS method, an alternative ranking methodology, is applied to rank EU countries based on their indicator values. This process will discern the countries that exhibit superior GKI indicators and establish the position of each observed EU nation in the ranking. The findings will highlight both the positive and negative aspects within the GKI for each country, pinpointing areas that necessitate enhancement and improvement.

This study is anticipated to identify critical factors influencing the positions of EU countries in the cultivation and application of the knowledge economy. It seeks to offer guidelines for the formulation of targeted policies and enhancement strategies. The objective extends beyond the academic realm, aiming to provide policymakers with vital insights for shaping the EU's trajectory within the global knowledge landscape. The contributions of this research are delineated as follows:

Firstly, a novel methodological approach for ranking countries based on their knowledge economy will be introduced. This approach will contribute a fresh perspective to the existing body of research. Secondly, the study's findings are expected to underscore the importance of specific indicators within the GKI that are crucial and in need of improvement. These findings will assist in directing focus to key areas for enhancing the knowledge economy. Thirdly, the establishment of a ranking system for EU countries based on these indicators will facilitate a deeper understanding of their respective standings. This, in turn, will enable EU nations to tailor their policies more effectively towards improving specific aspects of the knowledge economy.

However, the research is not without its limitations. The study's focus is exclusively on the GKI indicators for assessing the EU knowledge economy. This raises questions regarding the selection of these specific methods over other potential alternatives. It is acknowledged that the application of different methods could lead to variations in the ranking order, thus inviting discussions on the most optimal approaches. Such limitations are, however, inherent in research of this nature. Future studies are encouraged to explore alternative methodologies to evaluate their effectiveness in comparison with the methods used in this study.

2 Literature Review

The GKI, an annual publication developed to monitor the performance of countries in the knowledge economy, encompasses seven critical areas: secondary education, technical and vocational education and training, higher education, research, development and innovation, information and communication technology, economy, and the general stimulating environment [8]. The GKI, jointly published by the United Nations Development Program (UNDP) and the Mohammed Bin Rashid Al Maktoum Knowledge Foundation (MBRF), made its inaugural appearance in 2016 [9]. Since its introduction, the GKI has been extensively utilized in various scholarly analyses.

In his 2017 study, Ibrahim [10] employed GKI data to scrutinize the quality of higher education, a pivotal indicator within the index. His research was concentrated on assessing the efficacy of higher education, with a specific focus on the influence exerted by environmental factors and research and development on its evolution. The study emphasized the crucial role of higher education in advancing the knowledge economy. Furthermore, Altintaş [7] conducted an analysis ranking the Group of Seven (G7) countries, applying the Combined Compromise Solution (CoCoSo) and entropy methods. The findings were compared with those derived from the Evaluation based on Distance from Average Solution (EDAS), Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), and Gray Relational Analysis (GIA) methods. The results indicated that the the United States of America (US) and the United Kingdom (UK) exhibited the most favorable outcomes. Altintaş's research underscored the feasibility of employing multi-criteria analysis methods for country ranking, demonstrating their effectiveness in comparative evaluation.

In their research, Bilan et al. [2] applied GKI indicators to examine the influence of information and communication technology on the formation of the index. Regression analysis revealed a significant impact of this indicator on the GKI. Miranda [1] conducted an analysis of the GKI's trajectory during the COVID-19 pandemic, focusing on its implications for the vulnerability of certain countries in developing their knowledge economies. The pandemic period marked a transition from scientific cooperation to geopolitical competition, with nations utilizing the situation to fortify their knowledge-based positions, often at others' expense. Thus, this research offers a critical perspective on the post-pandemic state of the GKI in EU countries and their respective rankings. Djeflat [11] highlighted the role of the knowledge economy in fostering growth and competitiveness, considering the potential of initiating a knowledge economy, as exemplified by Algeria. This analysis incorporated the GKI index.

Decebal-Remus [12] concentrated on the quality of life in EU countries, studying consumer habits related to newspapers, radio, television, and the Internet. Employing the quality of life index and the human development index alongside the GKI, the research found that EU countries with a higher reliance on newspapers demonstrated a superior quality of life. Buchinskaia [13] addressed the issue of digital inequality, underscoring its significant role in a nation's knowledge development. The research posited that technology penetration does not necessarily correlate with the digitization process, drawing insights from the GKI. The literature demonstrates several prevailing approaches in the utilization of the GKI. The first is the comprehensive application of the GKI in research [1, 3]. Another method involves integrating GKI indicators as variables in studies [11, 12]. A third approach scrutinizes individual indicators, analyzing their interrelated impacts [2]. These methodologies underscore the versatility and applicability of GKI indicators in a wide array of research contexts, particularly in studies focusing on the evolution of the knowledge economy.

3 Methodology

In this research, the following methodological phases were methodically executed:

Phase 1: Data collection and preparation for analysis.

Phase 2: Determination of indicator weights using the entropy method.

Phase 3: Ranking of EU countries using compromise analysis.

Phase 4: Comparative analysis using different multi-criteria methods.

Phase 5: Sensitivity analysis.

In the initial phase of this research, the GKI from 2023 was systematically downloaded, and data pertaining to the primary indicators for EU countries were extracted. This process led to the formation of the initial decision-making matrix, encompassing seven criteria representing the main indicators of the GKI and 27 alternatives, each corresponding to an EU country. This matrix served as the foundational basis for the subsequent application of multi-criteria analysis methods. It is imperative to acknowledge that in research employing multi-criteria methods, this preparatory stage is of paramount importance. It involves the critical task of calculating the weights from this matrix, which underpins the rankings and provides the groundwork for both comparative and sensitivity analyses.

In contrast to the approach adopted in the original GKI report, where the first six indicators were uniformly assigned a weight of 0.15 and the final indicator a weight of 0.10 [8], this study utilized the Entropy method to objectively determine the weights of the criteria. The Entropy method, widely acknowledged for its objective weight determination capabilities [14], was meticulously applied as follows [15]:

Step 1: Formation of the initial decision matrix.

Step 2: Normalization of the initial decision matrix.

$$n'_{ij} = \frac{x_{ij}}{x_{j\,\max}} \tag{1}$$

where, $x_{j\,\max}$ is the maximum value of the alternative for certain criteria.

Step 3: Determination of the entropy value e_j.

$$e_j = -k \sum_{i=1}^{n} \ln n_{ij} \cdot n_{ij}, j = 1, 2, \ldots, m \tag{2}$$

where, the value of k is calculated by the formula $k = 1/\ln n$, with n representing the number of criteria.

Step 4: Calculation of the degree of divergence d_j.

$$d_j = 1 - e_j, j = 1, 2, \ldots, m \tag{3}$$

Step 5: Calculation of final criteria weights.

$$w_j = \frac{d_j}{\sum_{j=1}^{m} d_j} \tag{4}$$

Upon the computation of the weights for the main GKI indicators through the entropy method, the subsequent phase focused on the ranking of EU countries. This ranking was based on the GKI indicator values and the weights derived from the entropy method. The initial decision-making matrix, already established, and the weights of the criteria determined in the second phase, were pivotal in this process. The CRADIS method, formulated by Puška et al. [16], was employed for this purpose. The essence of the CRADIS method lies in ascertaining deviations relative to ideal and anti-ideal solutions and in comparison to optimal alternatives. The methodological steps in this phase were as follows:

Step 1: Formation of the initial decision matrix.

Step 2: Normalization of the initial decision matrix. The normalization process followed the same formula utilized in the entropy method.

Step 3: Weighted decision matrix.

$$v_{ij} = n_{ij} \times w_j \tag{5}$$

Step 4: Determination of ideal and anti-ideal solutions. The ideal solution was identified as the highest value v_{ij}, whereas the anti-ideal solution was the lowest value v_{ij}.

$$t_i = \max \tilde{v}_{ij} \tag{6}$$

$$t_{ai} = \min \tilde{v}_{ij} \tag{7}$$

Step 5: Calculation of deviations from ideal and anti-ideal solutions.

$$d^+ = t_i - \tilde{v}_{ij} \tag{8}$$

$$d^- = \tilde{v}_{ij} - t_{ai} \tag{9}$$

Step 6: Formation of the ideal (A_{ia}) and anti-ideal optimal alternatives (A_{aia}).

Step 7: Calculation of the sum of deviations.

$$s_i^+ = \sum_{j=1}^{n} d^+ \tag{10}$$

$$s_i^- = \sum_{j=1}^{n} d^- \tag{11}$$

Step 8: Calculation of the utility function.

$$K_i^+ = \frac{s_0^+}{s_i^+} \tag{12}$$

$$K_i^- = \frac{s_i^-}{s_0^-} \tag{13}$$

Step 9: Determination of the CRADIS value.

$$Q_i = \frac{K_i^+ + K_i^+}{2} \tag{14}$$

The best ranked alternative is the one with the highest value Q_i.

Following the determination of the EU countries' rankings based on the GKI, the subsequent phase of this research entailed a comparative analysis using different multi-criteria methods. The objective was to investigate whether alternative methods would yield divergent rankings, despite using the same initial decision matrix and criteria weights. This exploration was deemed necessary due to the distinct steps involved in each method, particularly in terms of normalization and weight assignment. Consequently, three additional multi-criteria analysis methods were incorporated: Simple Additive Weighting (SAW), Additive Ratio Assessment (ARAS), and Multi-Attributive Border Approximation area Comparison (MABAC). The SAW method, which adopts the same normalization process as CRADIS, was utilized to assess if consistent rankings are achieved under identical normalization but varied procedural steps. Conversely, the ARAS and MABAC methods, which involve alternative normalization techniques, facilitated an evaluation of the impact of different initial normalization steps on the ranking outcomes. A lack of substantial deviations in the rankings would corroborate the results obtained through the CRADIS method.

The final phase in this research methodology involved conducting a sensitivity analysis. This critical step utilized data from the initial phase, specifically the initial decision matrix, and incorporated information regarding the evolving weights of criteria from subsequent phases. The sensitivity analysis was built upon the application of the CRADIS method, previously established in the third phase of this research. While the comparative analysis was focused on determining the influence of individual methodological steps on the ranking of EU countries, the sensitivity analysis aimed to explore the extent to which variations in the weights of criteria impacted the countries' rankings in the GKI [17]. Several approaches exist for conducting sensitivity analysis. In this study, the approach entailed systematically reducing the weights of individual criteria. The reduction was executed in increments of 30%, continuing until the weight of each criterion reached only 10% of its initial value. This approach diverged from other studies, which often implemented a standard 15% change for each criterion [18]. However, findings from previous research have indicated that more pronounced shifts in rankings typically occur with substantial reductions in criterion weight. Therefore, this study applied only three changes at higher percentages to each of the seven criteria, culminating in a total of 21 distinct scenarios.

In acknowledging the methodologies adopted in this research, it is pertinent to outline their limitations. The Entropy method, utilized for calculating the weights of the GKI indicators, despite its widespread application, encounters a limitation in the determination of n for the calculation of k. Ambiguity exists in whether 'n' should represent the number of alternatives or the number of criteria, as interpretations vary across different studies. Furthermore, the incorporation of the natural logarithm in the calculation process adds a layer of complexity to the determination of criterion weights. Although modern spreadsheet programs facilitate the computation process, the entropy method requires a more extensive series of calculations compared to other methods. The CRADIS method, employed for ranking the EU countries, is characterized by a more intricate process compared to the methods used in the comparative analysis. This complexity stems from the numerous steps involved, including the determination of deviations from ideal and anti-ideal solutions, identification of optimal alternatives, and the computation of the utility function. The CRADIS method integrates individual calculation elements from other multi-criteria analysis methods. It adopts the approach of deviation from ideal and anti-ideal solutions from the TOPSIS and Measurement of Alternatives and Ranking according to the Compromise Solution (MARCOS) methods, optimal alternatives from the ARAS method, and the utility function from the MARCOS method. However, the CRADIS method distinguishes itself by uniquely amalgamating these approaches from various methodologies, which substantiates its selection for this study.

4 Results

In accordance with the methodologies outlined, the initial step undertaken in this research involved the formation of the decision-making matrix. This matrix was constructed based on the 2023 GKI data for EU countries (Table 1). This matrix constituted the foundational element for the subsequent multi-criteria analysis.

Following the establishment of the initial decision-making matrix, the next procedural step in this research was the normalization of this matrix. This normalization was conducted by first identifying the highest values for each criterion across the EU countries. Subsequently, the elements of the initial decision matrix were divided by these maximum values. The resulting normalized decision matrix is presented in Table 2.

Utilizing the normalized decision matrix, the subsequent step involved calculating the criteria weights for the CRADIS method, beginning with the entropy method. In this phase, the natural logarithm (ln) values were first computed, followed by their multiplication with the normalized values from the initial decision matrix. These products were then combined and multiplied by the negative value of the k value, calculated as $k = 1/\ln 7 = 0.5139$. The entropy value (e_j) was subsequently derived from this process. The divergence value was then ascertained, culminating in the determination of the weights of the criteria, as shown in Table 3.

Notably, the weight of criterion C4 (research, development and innovation) is markedly higher than that of criterion C1 (pre-university education), being 13.21 times more significant. This disparity stems from the greater dispersion of values for criterion C4 across EU countries, warranting a higher weight compared to other criteria. Criterion C4 notably influences 37.01% of the final ranking, underscoring its critical importance in the GKI ranking of EU countries. The weights derived from the entropy method indicate that certain criteria exert a more pronounced impact on the final ranking, which aligns with the objectives of this research. The variation in weights reflects the differing importance of criteria, suggesting that not all criteria should bear equal weight. Criteria that consistently score high across countries, indicating less immediate need for improvement, contrast with those where considerable disparities exist, warranting more focused attention. These findings offer valuable insights for policymakers in EU countries, highlighting the indicators that demand prioritization. As a result, these criteria weights should guide the formation of strategic development policies within these countries, with a specific focus on enhancing aspects of the knowledge economy identified as most critical.

Table 1. Initial decision-making matrix

	Pre-University Education	**Technical and Vocational Education and Training**	**Higher Education**	**Research, Development and Innovation**	**Information and Communications Technology**	**Economy**	**Enabling Environment**
	C1	C2	C3	C4	C5	C6	C7
Austria	79.60	67.40	64.70	43.50	66.10	67.80	79.40
Belgium	84.00	64.90	63.20	43.70	59.80	67.60	78.00
Bulgaria	69.80	58.70	58.60	34.10	56.50	55.80	61.60
Cyprus	77.50	50.60	67.10	41.70	65.10	55.30	68.90
Croatia	74.00	60.70	59.50	32.10	57.60	58.30	68.40
Czech Republic	83.10	63.40	59.10	39.10	55.80	65.70	73.90
Denmark	79.80	57.50	63.50	50.30	70.80	73.60	83.40
Estonia	79.90	64.20	62.50	43.30	71.10	63.40	76.50
Finland	84.30	68.20	61.30	50.70	71.80	66.70	85.80
France	78.50	55.20	53.50	45.70	65.20	65.50	75.30
Germany	75.70	63.70	61.10	47.30	61.90	66.50	79.40
Greece	72.80	47.00	47.20	34.80	53.00	52.50	63.90
Hungary	70.60	67.10	47.80	34.90	56.70	66.20	67.00
Ireland	70.40	60.30	55.30	42.90	62.40	72.30	81.80
Italy	75.40	62.40	52.40	42.30	55.50	59.70	68.70
Latvia	80.50	62.80	59.30	32.60	63.10	63.30	71.70
Lithuania	79.30	58.20	56.90	32.60	62.20	62.40	73.90
Luxembourg	77.20	64.10	66.40	45.90	72.60	65.40	82.40
Malta	78.20	52.70	58.00	46.70	71.50	68.50	73.80
Netherlands	83.80	68.10	63.00	48.80	71.60	65.60	80.60
Poland	83.40	55.30	54.80	31.60	57.90	57.80	69.30
Portugal	85.70	62.10	63.30	34.90	57.30	59.50	77.20
Romania	60.20	57.70	55.00	32.00	54.20	58.90	64.60
Slovakia	80.10	69.10	58.30	30.50	54.20	56.60	69.00
Slovenia	82.40	65.50	61.40	39.80	63.70	62.60	75.50
Spain	79.10	59.70	55.40	37.40	62.00	60.40	73.10
Sweden	82.30	61.20	62.40	54.70	72.40	68.10	85.70

Upon the calculation of weights using the Entropy method, the ranking of EU countries was conducted through the CRADIS method. In this process, the initial steps involved normalization of the decision matrix, akin to those in the entropy method. Subsequently, the focus shifted to the third step, involving the intensification of the normalized decision matrix. This step entailed multiplying the normalized values in the decision matrix with their corresponding weights, derived from the entropy method. For instance, the normalized values for criterion C1 were multiplied by the weight of C1, and similarly for other criteria (Table 4). Following this, ideal and anti-ideal solutions were identified: the ideal solution being the largest value in the weighted decision matrix, and the anti-ideal solution being the smallest. The differences between the values in the weighted decision matrix and the ideal solution were calculated, as well as the deviations from the anti-ideal solution. This led to the formation of two matrices representing deviations from the ideal and anti-ideal solutions.

In the application of the CRADIS method, the determination of ideal and anti-ideal solutions was conducted as a pivotal step. The ideal solution was identified as the highest value within the weighted decision matrix, whereas the anti-ideal solution corresponded to the lowest value in this matrix. Subsequently, the deviation of the matrix values from both the ideal and anti-ideal solutions was calculated, resulting in the formation of two distinct decision matrices. These matrices effectively encapsulated the deviations from the ideal and anti-ideal solutions. Further analysis involved expanding these matrices with optimal alternatives. An optimal alternative was determined based on the minimum deviation values from the ideal solution and the maximum deviation values from the anti-ideal solution. This process culminated in the calculation of aggregate values for the EU countries under observation and the computation of membership functions. For the ideal solution-related membership function, the value of each optimal alternative was divided by the respective cumulative deviation values from the ideal solution. Similarly, for the anti-ideal solution, the sum of deviations of alternatives was divided by the optimal alternative. The culmination of the CRADIS method involved deriving the final value through averaging the values of the membership functions (Table 5). According to the results obtained via this method, Sweden emerged as the highest-ranking country, followed by Finland, with Greece being positioned as the lowest-ranking amongst all EU countries. To validate these findings, a comparative analysis was undertaken with other multi-criteria analysis methods. This comparison aimed to confirm the consistency and reliability of the rankings produced by the CRADIS method.

Table 2. Normalized initial decision matrix

	C1	C2	C3	C4	C5	C6	C7
Austria	0.929	0.975	0.964	0.795	0.910	0.921	0.925
Belgium	0.980	0.939	0.942	0.799	0.824	0.918	0.909
Bulgaria	0.814	0.849	0.873	0.623	0.778	0.758	0.718
Cyprus	0.904	0.732	1.000	0.762	0.897	0.751	0.803
Croatia	0.863	0.878	0.887	0.587	0.793	0.792	0.797
Czech Republic	0.970	0.918	0.881	0.715	0.769	0.893	0.861
Denmark	0.931	0.832	0.946	0.920	0.975	1.000	0.972
Estonia	0.932	0.929	0.931	0.792	0.979	0.861	0.892
Finland	0.984	0.987	0.914	0.927	0.989	0.906	1.000
France	0.916	0.799	0.797	0.835	0.898	0.890	0.878
Germany	0.883	0.922	0.911	0.865	0.853	0.904	0.925
Greece	0.849	0.680	0.703	0.636	0.730	0.713	0.745
Hungary	0.824	0.971	0.712	0.638	0.781	0.899	0.781
Ireland	0.821	0.873	0.824	0.784	0.860	0.982	0.953
Italy	0.880	0.903	0.781	0.773	0.764	0.811	0.801
Latvia	0.939	0.909	0.884	0.596	0.869	0.860	0.836
Lithuania	0.925	0.842	0.848	0.596	0.857	0.848	0.861
Luxembourg	0.901	0.928	0.990	0.839	1.000	0.889	0.960
Malta	0.912	0.763	0.864	0.854	0.985	0.931	0.860
Netherlands	0.978	0.986	0.939	0.892	0.986	0.891	0.939
Poland	0.973	0.800	0.817	0.578	0.798	0.785	0.808
Portugal	1.000	0.899	0.943	0.638	0.789	0.808	0.900
Romania	0.702	0.835	0.820	0.585	0.747	0.800	0.753
Slovakia	0.935	1.000	0.869	0.558	0.747	0.769	0.804
Slovenia	0.961	0.948	0.915	0.728	0.877	0.851	0.880
Spain	0.923	0.864	0.826	0.684	0.854	0.821	0.852
Sweden	0.960	0.886	0.930	1.000	0.997	0.925	0.999

Table 3. Weights of the criteria calculated by the entropy method

	C1	C2	C3	C4	C5	C6	C7
e_i	1.1469	1.4721	1.5384	2.9412	1.7008	1.7775	1.6683
d_i	-0.1469	-0.4721	-0.5384	-1.9412	-0.7008	-0.7775	-0.6683
w	0.0280	0.0900	0.1027	0.3701	0.1336	0.1482	0.1274

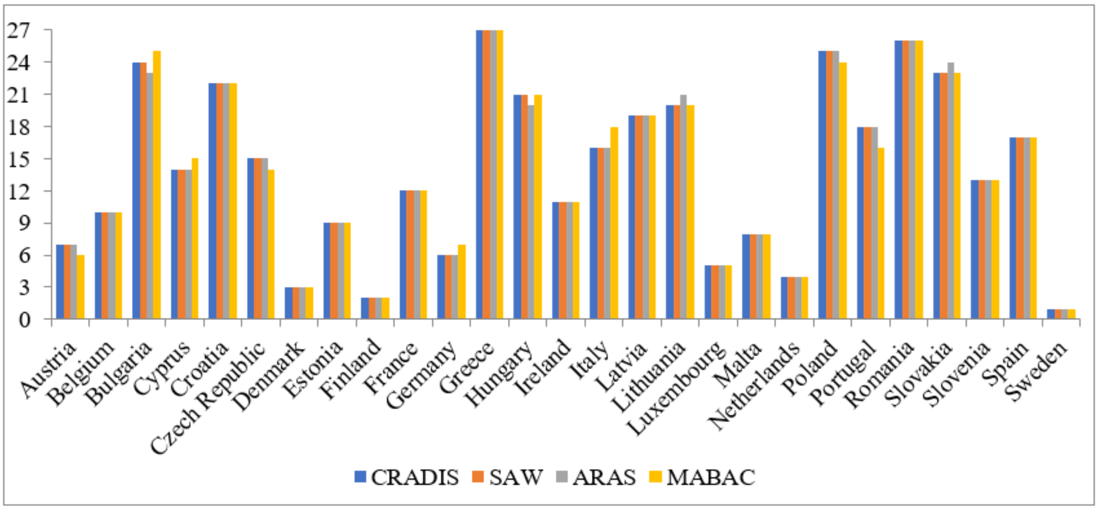

Figure 1. Comparative analysis of different multi-criteria methods

Table 4. Weighted decision matrix

	C1	C2	C3	C4	C5	C6	C7
Austria	0.0260	0.0878	0.0990	0.2943	0.1216	0.1365	0.1179
Belgium	0.0275	0.0845	0.0967	0.2957	0.1100	0.1361	0.1158
Bulgaria	0.0228	0.0765	0.0896	0.2307	0.1040	0.1124	0.0915
Cyprus	0.0253	0.0659	0.1027	0.2821	0.1198	0.1114	0.1023
Croatia	0.0242	0.0791	0.0910	0.2172	0.1060	0.1174	0.1016
Czech Republic	0.0272	0.0826	0.0904	0.2645	0.1027	0.1323	0.1097
Denmark	0.0261	0.0749	0.0971	0.3403	0.1303	0.1482	0.1239
Estonia	0.0261	0.0836	0.0956	0.2930	0.1308	0.1277	0.1136
Finland	0.0276	0.0888	0.0938	0.3430	0.1321	0.1343	0.1274
France	0.0257	0.0719	0.0818	0.3092	0.1200	0.1319	0.1118
Germany	0.0247	0.0830	0.0935	0.3200	0.1139	0.1339	0.1179
Greece	0.0238	0.0612	0.0722	0.2354	0.0975	0.1057	0.0949
Hungary	0.0231	0.0874	0.0731	0.2361	0.1043	0.1333	0.0995
Ireland	0.0230	0.0785	0.0846	0.2902	0.1148	0.1456	0.1215
Italy	0.0246	0.0813	0.0802	0.2862	0.1021	0.1202	0.1020
Latvia	0.0263	0.0818	0.0907	0.2206	0.1161	0.1275	0.1065
Lithuania	0.0259	0.0758	0.0870	0.2206	0.1145	0.1257	0.1097
Luxembourg	0.0252	0.0835	0.1016	0.3105	0.1336	0.1317	0.1224
Malta	0.0256	0.0686	0.0887	0.3160	0.1316	0.1380	0.1096
Netherlands	0.0274	0.0887	0.0964	0.3302	0.1318	0.1321	0.1197
Poland	0.0273	0.0720	0.0838	0.2138	0.1066	0.1164	0.1029
Portugal	0.0280	0.0809	0.0968	0.2361	0.1054	0.1198	0.1146
Romania	0.0197	0.0752	0.0841	0.2165	0.0997	0.1186	0.0959
Slovakia	0.0262	0.0900	0.0892	0.2064	0.0997	0.1140	0.1025
Slovenia	0.0269	0.0853	0.0939	0.2693	0.1172	0.1261	0.1121
Spain	0.0259	0.0778	0.0848	0.2530	0.1141	0.1216	0.1086
Sweden	0.0269	0.0797	0.0955	0.3701	0.1332	0.1371	0.1273

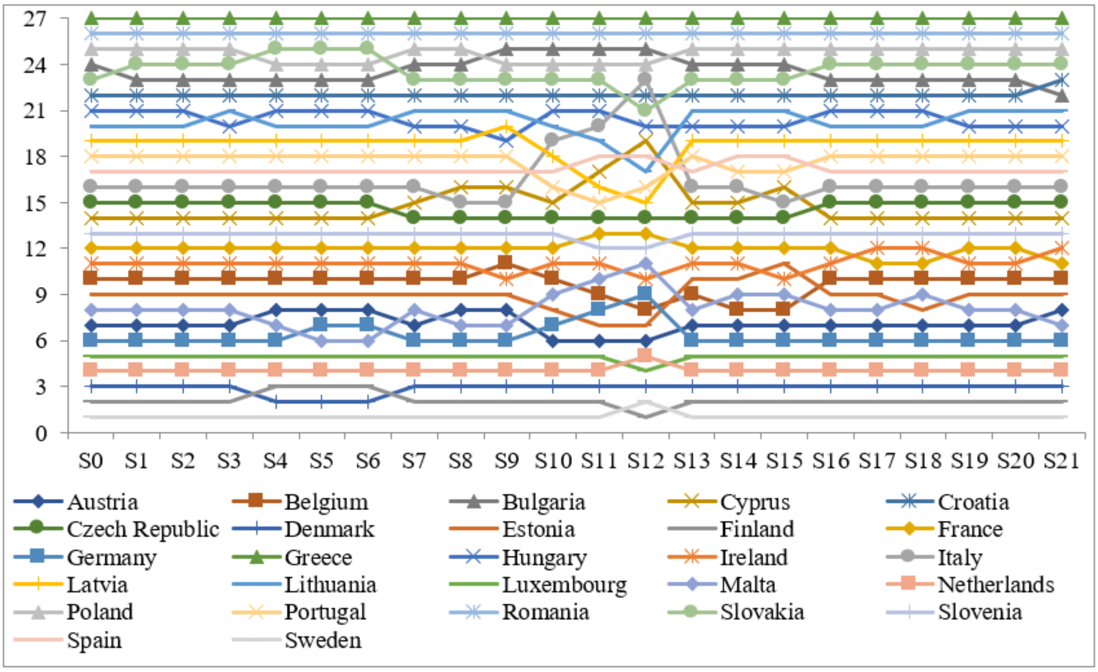

Figure 2. Results of the sensitivity analysis

In this study, the outcomes derived from the CRADIS method were compared with those obtained via the SAW, ARAS, and MABAC methods. The rationale for selecting these methods is as follows: The SAW method, known for its simplicity, often yields results analogous to more complex multi-criteria analysis methods and was used with the same normalization as CRADIS. ARAS was chosen due to its relatively straightforward approach but with a different normalization technique. MABAC, distinguished by its unique normalization and weighting procedures, was included to examine the influence of these factors on the ranking of EU countries in terms of the GKI. The results of this comparative analysis, as illustrated in Figure 1, indicated that the rankings provided by the SAW and CRADIS methods were identical. However, the rankings from the ARAS and MABAC methods displayed partial variations.

Table 5. Deviation of alternatives from ideal and anti-ideal solutions, utility functions and ranking of alternatives

Country	s^+	s^-	K_i^+	K_i^-	Q_i	Rank
Austria	1.7074	0.7454	0.9316	0.8645	0.8981	7
Belgium	1.7242	0.7286	0.9225	0.8450	0.8838	10
Bulgaria	1.8631	0.5897	0.8537	0.6839	0.7688	24
Cyprus	1.7811	0.6718	0.8930	0.7791	0.8361	14
Croatia	1.8541	0.5987	0.8579	0.6943	0.7761	22
Republic	1.7811	0.6717	0.8930	0.7790	0.8360	15
Denmark	1.6498	0.8031	0.9641	0.9314	0.9477	3
Estonia	1.7201	0.7327	0.9247	0.8497	0.8872	9
Finland	1.6435	0.8093	0.9678	0.9386	0.9532	2
France	1.7383	0.7146	0.9150	0.8287	0.8719	12
Germany	1.7036	0.7492	0.9336	0.8689	0.9013	6
Greece	1.8997	0.5531	0.8373	0.6414	0.7393	27
Hungary	1.8337	0.6191	0.8674	0.7181	0.7927	21
Ireland	1.7323	0.7206	0.9182	0.8357	0.8769	11
Italy	1.7939	0.6589	0.8867	0.7642	0.8254	16
Latvia	1.8211	0.6317	0.8734	0.7326	0.8030	19
Lithuania	1.8314	0.6215	0.8685	0.7207	0.7946	20
Luxembourg	1.6820	0.7708	0.9456	0.8939	0.9198	5
Malta	1.7126	0.7403	0.9288	0.8585	0.8937	8
Netherlands	1.6644	0.7885	0.9557	0.9144	0.9350	4
Poland	1.8678	0.5850	0.8516	0.6785	0.7650	25
Portugal	1.8088	0.6440	0.8794	0.7469	0.8131	18
Romania	1.8808	0.5720	0.8457	0.6634	0.7545	26
Slovakia	1.8626	0.5902	0.8539	0.6845	0.7692	23
Slovenia	1.7597	0.6931	0.9039	0.8039	0.8539	13
Spain	1.8049	0.6479	0.8813	0.7515	0.8164	17
Sweden	1.6208	0.8321	0.9814	0.9650	0.9732	1
Austria	1.7074	0.7454	0.9316	0.8645	0.8981	7
S_0	1.5906	0.8622				

Table 6. Results of correlation analysis

	CRADIS	SAW	ARAS	MABAC
CRADIS	1.0000	1.0000	0,9988	0.9957
SAW		1.0000	0,9988	0,9957
ARAS			1,0000	0,9939
MABAC				1,0000

This analysis revealed that the ranking of the sixth-placed EU country shifted across methods. Other countries also experienced changes in ranking, but these were not drastic, as corroborated by the results of a correlation analysis (Table 6). This correlation analysis underscored a strong concordance between the rankings of all these methods, indicating minimal significant differences. Notably, the rankings from the MABAC method exhibited a slightly greater deviation compared to the other methods, yet this difference was not substantial. Consequently, the findings from the CRADIS method are deemed reliable and acceptable.

Following the comparative analysis, the first sensitivity analysis was conducted. As delineated in the methodology, 21 scenarios were implemented, wherein the weights of the criteria were individually adjusted to ascertain their impact on the ranking of EU countries in terms of the GKI. The analysis revealed that all countries, except the lowest-ranked, experienced a change in their ranking. This shift is attributable to the varying strengths and weaknesses of countries in the GKI indicators. Notably, Italy exhibited the most significant drop in ranking across 12 scenarios, particularly in a scenario where only 10% of the original weight of criterion C4 was considered. The reduction in the weight of this criterion led to Italy's decline from the 16^{th} to the 23^{rd} position, as this country had performed better in this criterion relative to others. Conversely, in the same scenario, Finland surpassed Sweden in the ranking.

The sensitivity analysis (Figure 2) underscored that in most scenarios, countries retained their original rankings, as determined by the initial weights. The most pronounced changes were observed in scenario S12, where the weight of criterion C4, which initially held the highest weight, was markedly decreased. In other scenarios, where the weight of less significant criteria was altered, the shifts in ranking orders were relatively minor. This analysis offers critical insights for policy-making in EU countries. When a country's ranking improved as the weight of a certain criterion was lowered, it suggested areas requiring enhancement. On the other hand, a deterioration in ranking indicated strong performance in that criterion, signaling a need to focus on improving other areas.

5 Discussion

This research undertook a nuanced approach to ranking EU countries based on the GKI. Contrary to the GKI report's methodology, which assigns uniform weights to most criteria, this study determined criteria weights based on variations in individual criterion values across EU countries. In the GKI report, the first six criteria are equally weighted at 15%, and the last criterion is given a 10% weight, as per expert consensus. However, this study's findings revealed a notably reduced influence of the first criterion, pre-university education, on the GKI ranking of EU countries. The entropy value for this criterion was closest to one, resulting in a minimal determination value compared to other criteria. Furthermore, a larger number of countries exhibited commendable performance in this criterion [19], contributing to a lower average value relative to other criteria. Conversely, a criterion with fewer countries excelling received a higher weight. This analysis advocates for the weighting of individual indicator values to influence country rankings in the GKI, rather than assigning near-equal weight to all indicators. Future research should examine the implications of this discrepancy and provide recommendations for refining the GKI report's accuracy in reflecting the true standing of countries' GKI.

Following the weight determination, the CRADIS method was employed for ranking countries in terms of GKI. The selection of the CRADIS method was based on several factors. Primarily, it belongs to the newer multi-criteria analysis methods, increasingly utilized in alternative ranking processes. Its outcomes have consistently shown minimal deviation from results of other methods, reinforcing the validity of its application. Additionally, the CRADIS method uniquely combines the characteristics of several multi-criteria analysis methods [16]. It first assesses rankings based on deviations from ideal and anti-ideal solutions and then considers optimal alternatives. Unlike direct replication, the CRADIS method adapts various steps from other methods, contributing to its distinct methodology. The application of multi-criteria analysis methods does not guarantee flawless outcomes. Instead, these methods represent a compromise among individual criterion values, acknowledging that it is often challenging for an alternative to excel in every criterion. When an alternative clearly outperforms others across all criteria, further analysis may become redundant. The same principle applies to the results obtained from these methods; no single method can claim to deliver perfect outcomes, as encompassing all individual aspects within one method is impractical. Consequently, these methods are founded on specific analyses at different stages. The CRADIS method, in particular, was designed to integrate steps from various methods, not merely replicating them but modifying them to enhance the method's uniqueness. Moreover, the CRADIS method involves a greater number of steps and calculations compared to other methods, necessitating a careful balance to achieve the most optimal results.

The research outcomes positioned Sweden at the forefront in the GKI, closely followed by Finland. This ranking was primarily attributed to Sweden's superior performance in criterion C4 (research, development and innovation), which was identified as crucial in this study's ranking process. The significance of this criterion was further underscored in the sensitivity analysis, wherein a substantial reduction in its weight led to Finland surpassing Sweden in the ranking. This result indicates a pivotal focus for Finland to ascend in GKI: the enhancement of their capabilities in research, development, and innovation. Conversely, Greece and Romania consistently maintained their respective rankings, regardless of variations in the weights of individual criteria [20]. This persistence suggests that for these countries to improve their GKI standings, comprehensive enhancements across multiple criteria are essential [21]. Their consistent rankings, irrespective of weight adjustments, underline the need for multifaceted developmental strategies to uplift their overall performance in the GKI.

In this research, a comparative analysis was conducted employing various multi-criteria analysis methods, applied to the same dataset as the CRADIS method. The SAW method, for instance, yielded an identical rank order as that of CRADIS. This similarity is likely attributed to the analogous normalization processes employed by both methods. Initially, these methods adhere to a common sequence of three steps; however, they diverge subsequently, particularly in the formation of the ranking order in the case of the SAW method. Conversely, the MABAC method exhibited significant differences in the rankings. This variation can be primarily ascribed to MABAC's distinct approach to normalizing the decision matrix. Unlike CRADIS, which assigns the highest value to one specific alternative per criterion, MABAC employs a normalization scale that ranges from zero (for the lowest alternative value) to one (for the highest). This fundamental difference in normalization processes results in a more pronounced disparity compared to the variations observed with the ARAS method. Additionally, the weighting process in MABAC is unique; it involves adding the weight to the product of the normalized decision matrix and the corresponding weights, thus creating a distinct weighted decision matrix. This methodology stands in contrast to other methods, contributing to the notable variance in the results. Furthermore, MABAC calculates deviations with respect to the average value of the alternatives, rather than ideal values, which further distinguishes its approach from other multi-criteria analysis methods. These observations underscore the need for future research to delve into the factors influencing country rankings in the GKI. This exploration should encompass criteria weight, normalization methods, analysis techniques, and the complexities inherent in normalized decision matrices. Such comprehensive investigations aim to provide EU countries with valuable insights into areas necessitating improvements to enhance their GKI values, thereby fostering advancement and competitiveness on a global scale.

6 Conclusions

This research was conducted with the objective of determining the ranking of EU countries in terms of the GKI, utilizing various multi-criteria analysis methods. The resulting rankings differ notably from those in the original GKI report due to the distinct emphasis placed on individual indicators. The primary distinction is observed in the weighting of these indicators for GKI computation. Unlike the original report, which does not consider internal values of indicators, this study employed the entropy method for the objective determination of criterion weights, leading to different outcomes, particularly where Sweden emerged as the top-ranked country. The application of the entropy method, a widely recognized and validated technique for weight determination, has raised questions about its impact on the rankings. In response to these concerns, it is crucial to explore rankings derived from subjectively determined weights and examine their influence on the GKI rankings of EU countries. The rationale for selecting the entropy method was underpinned by the understanding that countries exhibit varying performances across the set GKI indicators. Not all indicators are equally significant, and the method aimed to identify those with the broadest dispersion among countries, assigning them greater weight. Should a different set of countries be analyzed, the importance assigned to specific indicators might vary, reflecting the performance of those countries. In light of these findings, the countries in focus should prioritize the enhancement of indicators that hold higher weights to improve their competitive stance in the global market. Future research should investigate alternative objective methods for determining criterion weights, such as the CRiteria Importance Through Intercriteria Correlation (CRITIC) or MEthod based on the Removal Effects of Criteria (MEREC) methods. Such exploration is essential to ascertain whether these methods also emphasize particular criteria over others. The potential lies in developing or refining existing methodologies to gain a deeper understanding of how criterion weights are established and their implications on country rankings in the GKI.

The findings of this research, which focused on the ranking of EU countries in the GKI, underscored the significant influence of criteria weights and normalization methods. This was partially evidenced by the outcomes of the comparative analysis conducted. Future research endeavors should prioritize investigating various normalization techniques on the initial decision matrix to assess their impact on the GKI rankings of EU countries. Moreover, while the CRADIS method exhibited alignment with other multi-criteria analysis methods, it is recommended that subsequent studies incorporate a broader range of methods not explored in this research to further validate these results. Future investigations should critically examine the effect of diverse normalization methods on the ranking order. This could involve applying the same method with different normalization techniques or using varied methods while maintaining consistent normalization. Such an approach would shed light on the extent to which normalization methods influence country rankings within the GKI framework. Utilizing the flexibility of the CRADIS method to accommodate different normalization techniques will be crucial in understanding its specific impact on the GKI rankings of EU countries. Additionally, while the CRADIS method has demonstrated minimal deviation from other established methodologies, reinforcing its compatibility, its continuous application in future research warrants ongoing validation and justification.

This study, despite the potential limitations that might affect the GKI rankings of EU countries, has provided valuable insights into each country's standing relative to others. It has identified specific criteria where notable disparities among countries are evident. This highlights the areas where improvements are necessary for countries to enhance their rankings within the EU. These research findings should act as a driving force for the development and progress of EU countries, aiming to elevate their GKI values and strengthen their competitiveness on a global scale.

Author Contributions

Conceptualization, A.P.; and A.Š.; methodology, A.P.; software, I.H.; validation, A.P. and A.Š.; formal analysis, A.P.; investigation, I.H.; resources, A.Š.; data curation, A.P.; writing—original draft preparation, A.P.; writ-

ing—review and editing, A.Š.; visualization, A.Š.; supervision, I.H.; project administration, A.P.; funding acquisition, A.P. All authors have read and agreed to the published version of the manuscript.

Data Availability

The data used to support the research findings are available from the corresponding author upon request.

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Conflicts of Interest

The authors declare no conflict of interest.

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