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Innovation Performance Analysis of G20 Countries: A Novel Integrated LOPCOW-MAIRCA MCDM Approach Including the COVID-19 Period

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ABSTRACT

Purpose: This study aims to examine the innovation performance of G20 countries in 2018-2022 with multi criteria decision making methods. When the 5-year performance was analyzed, it was also revealed whether the COVID-19 outbreak has an impact on the innovation performance of the countries.

Methodology: An integrated LOPCOW (Logarithmic Percentage Change-driven Objective Weighting) - MAIRCA (Multi Attribute Ideal-Real Comparative Analysis) method was applied in the study. First, the indicators representing innovation performance (institutions, human capital, and research, infrastructure, market sophistication, business sophistication, knowledge and technology outputs, creative outputs) was objectively weighted by the LOPCOW method. Then, the innovation performance of G20 countries was calculated with the MAIRCA method. Finally, a comparative analysis was also presented to support the findings.

Findings: As a result of the innovation performance analysis using multi criteria decision making methods, human capital, and research were found to be the most important indicators, and the United States was found to be the country with the best innovation performance. In the sensitivity and comparative analysis, it was concluded that the integrated LOPCOW-MAIRCA method provides robust outputs.

Originality: This study makes original contributions by analyzing the impact of the COVID-19 pandemic on the innovation performance of countries considering the 2018-2022 period and the integrated multi criteria decision making methods it uses that have not yet been applied in the literature.

Keywords*:* Innovation Productivity, Performance Analysis, MCDM, LOPCOW, MAIRCA.
JEL Codes: O31, H11, C44.

G20 Ülkelerinin İnovasyon Performans Analizi: COVID-19 Dönemini İçeren Yeni Bütünleşik LOPCOW-MAIRCA ÇKKV Yaklaşımı

ÖZET

Amaç: Bu çalışmada G20 ülkelerinin 2018-2022 yılları içerisindeki inovasyon performanslarının çok kriterli karar verme yöntemleri ile ele alınması amaçlanmaktadır. Ayrıca ülkelerin 5 yıllık performansları incelenerek COVID-19 salgınının inovasyon performanslarına bir etkisinin olup olmadığı da irdelenmektedir.

Yöntem: Çalışmada bütünleşik bir LOPCOW (LOgarithmic Percentage Change-driven Objective Weighting) - MAIRCA (Multi Attribute Ideal-Real Comparative Analysis) yöntemi uygulanmıştır. İlk olarak inovasyon performansını temsil eden göstergeler (kurumlar, beşerî sermaye ve araştırma, altyapı, pazar gelişmişliği, iş gelişmişliği, bilgi ve teknoloji çıktıları, yaratıcı çıktılar) LOPCOW yöntemi ile objektif olarak ağırlıklandırılmıştır. Daha sonra G20 ülkelerinin inovasyon performansları MAIRCA yöntemi ile hesaplanmıştır. Son olarak, elde edilen bulguları desteklemek için karşılaştırmalı bir analiz de sunulmuştur.

Bulgular: Çok kriterli karar verme yöntemleriyle ele alınan inovasyon performans analizi sonucunda, beşerî sermaye ve araştırma en önemli gösterge, Birleşik Devletler de en iyi inovasyon performansına sahip ülke olarak elde edilmiştir. Duyarlılık ve karşılaştırmalı analiz sonucunda ise, bütünleşik LOPCOW-MAIRCA yönteminin güçlü ve güvenilir çıktılar sunduğu sonucuna varılmıştır.

Özgünlük: Bu çalışma 2018-2022 dönemini göz önünde bulundurarak COVID-19 salgınının ülkelerin inovasyon performansı üzerindeki etkisini incelemesi ve kullandığı bütünleşik çok kriterli karar verme yöntemlerinin literatürde henüz uygulanmamış olması nedenleriyle özgün katkılar sunmaktadır.

Anahtar Kelimeler*:* İnovasyon Verimliliği, Performans Analizi, ÇKKV, LOPCOW, MAIRCA.
JEL Kodları: O31, H11, C44.

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1. INTRODUCTION

In a competitive world, countries need to be dynamic and sustainable by embracing technological developments. The construction of a competitive economy relies crucially on a nation's ability to foster a high degree of innovative activity. So, one of the decisive factors which determines the potential economic development is innovativeness (Alnafrah, 2021). Innovation is the process of creating new ideas, products, or services for adding value or solving problems within an organization. The concept of innovation plays a vital role in the evolution of industries and economic growth. It is widely acknowledged that innovation acts as a driving force behind productivity and competitiveness for organizations, regions, and nations (Murat, 2020). As globalization and technological advancements continue to accelerate, innovation has emerged as a fundamental pillar within a country’s production factors. Therefore, nations have to be aware of their innovation capabilities (Oturakci, 2023).

Measurement is vital for effective management. Evaluating innovation performance provides valuable insights into the level of national growth and welfare (Murat, 2020). Recognizing the current situation is necessary to determine innovation productivity and make recommendations for improvement. However, how to measure the performance of innovation is an ongoing discussion in the literature (Garcia-Bernabeu et al., 2020). Halkos and Tzeremes (2013) and Garcia-Bernabeu et al. (2020) summarize some challenges and various approaches for measuring innovation. Additionally, the literature presents numerous studies that explore comprehensive approaches to measuring innovation from various perspectives. The debate and challenge in innovation measurement include the identification of measurement indicators, their importance, and their impact on overall performance. Since innovation performance is a multi-dimensional structure, the assessment of innovation must be addressed inclusively. Evaluating and selecting the best option from a set of alternatives based on multiple criteria is known as a multi-criteria decision-making procedure. Therefore, it is clear that Multi Criteria Decision Making (MCDM) approaches can be one of the methodologies that can contribute to innovation measurement.

In this study, we aim to provide a robust framework for measuring the innovation performance of G20 countries from MCDM perspective for the period of 2018-2022. The study presents the integrated LOPCOW (LOgarithmic Percentage Change-driven Objective Weighting) - MAIRCA (Multi Attribute Ideal-Real Comparative Analysis) method. First, the indicators measuring innovation performance are objectively weighted with the LOPCOW method. Then, G20 countries are ranked in terms of their innovation performance using the MAIRCA method. Furthermore, sensitivity and a comparative analysis are conducted to assert that the proposed methodology is robust and valid. Although various studies have focused on countries' innovation performance, there is still a gap in the literature that our study will address. Particularly, our study will examine the period covering the COVID-19 pandemic, which has been the most catastrophic event in recent years in terms of both health and the economy. The impact of COVID-19 on countries' innovation performance has not been adequately examined in the existing literature. As stated by Jewell (2021), the investments in innovation reached record levels in 2019 prior to COVID-19 and it was expected that the innovation investments would likely suffer because of the pandemic. Nevertheless, throughout 2020, essential indicators of innovation investment continued to increase. This study examines the research question of how the 5-year innovation performance of G20 countries varies. Additionally, the research question revolves around the effects of COVID-19 on the innovation performance of countries as well. Our study will contribute to the literature by identifying the strengths, and weaknesses of countries and revealing dimensions committed to innovation-driven growth by considering the COVID-19 pandemic. Furthermore, the methodology (LOPCOW-MAIRCA) applied in our study has never been used in literature. The reason to prefer these methods is that the LOPCOW method is relatively novel and has not been integrated with the MAIRCA method yet. Also, since they are objective MCDM methods and they have notable features, an integrated LOPCOW-MAIRCA method is presented for the problem of innovation performance. Due to the novelty and uniqueness of the proposed methodology, a comprehensive two-step analysis was conducted to evaluate the reliability and validity of its generated results. In the first step, the influence of criteria weights, which directly affect the outcomes of MCDM methods, was assessed. Subsequently, in the second step, a comparison was drawn between the results yielded by the proposed methodology and those generated by other established MCDM methods in the existing literature. This process served to demonstrate the robustness of the proposed methodology in producing dependable and credible outcomes.

To address the research question, data including innovation indicators of countries is essential. Therefore, the reports published under the leadership of WIPO have been utilized to perform an objective analysis. Although each report includes 132 economies, our study will focus on the innovation performance of G20 countries. Since the member nations of the G20, representing around two-thirds of the world's population, account for approximately 85% of the global GDP and over 75% of the global trade (G20, 2023), we preferred to investigate G20 countries’ performance in terms of innovation. Furthermore, as stated in the report (G20, 2023), the Digital Economy Working Group was established in 2021 to reveal the digital potential of economies. This indicates that the analysis of innovation performance will provide valuable insights for policymakers to contribute to economic growth.

The aims and motivation of the study can be highlighted as follows:

- A novel integrated MCDM approach has been proposed for the innovation performance analysis of G20 countries.
- The proposed approach combines the LOPCOW and MAIRCA methods, which, to the best of our knowledge, have never been applied together before.
- The approach has been employed over 5 years, including the COVID-19 pandemic, to comprehensively investigate the performance of countries.
- The LOPCOW method has been utilized for weighting innovation performance indicators in an objective manner.
- The MAIRCA method has been used to rank countries for each year.
- The novel integrated methodology has been tested for robustness and validation through sensitivity and comparative analysis.

In the following sections of the study, the literature review, methodology, and findings sections will be presented respectively. Finally, the findings will be discussed in the conclusion section.

2. LITERATURE REVIEW

The literature review section is organized under 3 sub-headings by considering the topic and the methodology of this study. In the first part, the studies focused on innovation productivity were handled. In the second and third parts, the studies that applied the same methodologies were summarized.

2.1. Literature of Innovation Performance

The literature was reviewed by considering the “innovation productivity”, “innovation performance”, “multi-criteria decision-making”, “data envelopment analysis” keywords in Scopus database. Care was taken to ensure that the publications are up-to-date and high quality. It should be noted that the studies analyzed are not only conceptual studies, but also methodological ones. The summarized literature is given in Table 1 in the following.

According to Table 1, it is seen that there are studies that address innovation performance from different perspectives. For instance, city performance (Broekel et al. (2018), Deng et al. (2019), Chen et al. (2020), Garcia-Bernabeu et al. (2020)), country performance (Roszko-Wójtowicz and Białek (2016), Kaynak et al. (2017), Namazi and Mohammadi (2018), Alnafrah (2021), Aytekin et al. (2022), Robertson et al. (2023)) are topics which attract attention more. In addition, China, and Europe stand out as the most preferred locations in the studies focused on innovation performance in the literature. When the years covered in the studies are analyzed, it is seen that studies examining a specific time interval were last conducted in 2020. Moreover, innovation performance was analyzed by various methodologies. Data Envelopment Analysis (DEA), Multi-Criteria Decision-Making (MCDM), and statistical analysis such as Canonical correlation, PLS, SEM, Clustering, and Factor analysis were applied. Especially, DEA is the most preferred methodology in the literature on innovation performance. For a detailed review, one can see Narayanan et al. (2022). Moreover, it is obvious that recently published MCDM methods are very limited in the field of innovation.

It should be noted that there are still gaps in the literature in terms of both the scope (countries, timespan) and the methodology. One of the most striking gaps is that there is no study handling the COVID-19 effect on countries’ innovation performance. The other gap is that MCDM methods are very limited in the field of innovation performance. There are various novel objective MCDM methods that have not been applied yet. Therefore, we hope that our study contributes to the related literature in terms of both the scope and the methodology.

Table 1. Innovation performance studies

Author(s)	*Topic*	*Method*	*Timespan*
Robertson et al. (2023)	Analyzing the effect of knowledge-based dynamic capabilities of 129 countries	PLS-SEM	2019
Oturakci (2023)	Examination of the relationship between innovation factors	Canonical correlation	2013-2020
Erdin and Çağlar (2023)	Evaluation of 36 OECD countries' innovation efficiency	DEA	2019
Xu et al. (2023)	Measuring sustainable innovation performance of 27 EU countries	Slack-based DEA	2000-2017
Huang (2023)	Evaluation of Chinese manufacturing firms' innovation performance	Feasible Generalized Least Squares	2005-2007
Ecer and Aycin (2023)	Evaluation of G7 Countries' innovation performance	MEREC	2020
Aytekin et al. (2022)	Measuring of innovation efficiency for EU member and candidate countries	DEA-EATWIOS	2020
Ali et al. (2021)	Investigation of the impact on innovation performance for 24 Iraqi banks	CFA-SEM	2020
Yu et al. (2021)	Evaluation of high-tech companies' innovation performance in China	Dynamic Network DEA	2014-2017
Alnafrah (2021)	Assessment of national innovation systems for BRICS	Bias-corrected Network DEA	-
Chen et al. (2020)	Evaluation of city innovation capability in China, Liaoning	TOPSIS-ORM	2012-2016
Garcia-Bernabeu et al. (2020)	Analyzing regional innovation performance in Spain	MRP-WSCI	2019
Yin et al. (2020)	Measuring innovation performances in terms of green technology in China	Inter-indicator correlation & EFA & TOPSIS	-
Deng et al. (2019)	Investigation of innovation performance of Chinese Provinces	Super-efficiency DEA	2001-2016
Namazi and Mohammadi (2018)	Evaluation of innovation efficiency of 141 countries	TOPSIS/DEA	2015
Hájek et al. (2018)	Evaluation of innovation performance of European companies	Fuzzy TOPSIS & BSC	2010-2012
Broekel et al. (2018)	Evaluation of innovation efficiency of German regions	Shared-input DEA	1999-2008
Kaynak et al. (2017)	Evaluation of innovation performance of EU Candidate countries	Entropy-based TOPSIS	2012
Roszko-Wójtowicz and Białek (2016)	Measuring innovation performance of EU countries	Cluster & Factor analysis	2015
Lu et al. (2013)	Investigation of the effects of environmental strategic orientation on innovation performance	Fuzzy DEMATEL & Fuzzy DANP & VIKOR	-
Chang and Tzeng (2010)	Measuring innovation performances of high-tech industries	DEMATEL	-

2.2. Literature of the LOPCOW method

Due to LOPCOW being considered as one of the state-of-the-art MCDM methods, the number of studies in literature is limited. Table 2 presents the studies that applied the LOPCOW method.

Table 2. LOPCOW method studies

Author(s)	*Topic*	*Method*
Kahreman (2023)	Economic performance analysis in economic crisis period for G20 countries	LOPCOW, CoCoSo
Keleş (2023)	Evaluation of livable power center cities in G7 countries and Türkiye	LOPCOW, CRADIS
Ersoy (2023)	Performance analysis of Borsa İstanbul retail and trade sector	LOPCOW, RSMVC
Nila and Roy (2023)	Third-party logistics provider selection	Fuzzy LOPCOW, fuzzy FUCOM, fuzzy DOBI
Simic et al. (2023)	Material handling technology prioritizing for smart and sustainable warehouses	Neutrosophic LOPCOW, ARAS
Ecer et al. (2023a)	Sustainability performance analysis in urban transportation	IVFNN Delphi, LOPCOW, CoCoSo
Ulutaş et al. (2023)	Building insulation materials selection	PSI, MEREC, LOPCOW, MCRAT
Demir et al. (2023)	Open government performance analysis	LMAW, LOPCOW, WASPAS
Ecer et al. (2023b)	Unmanned aerial vehicle performance assessment	q-rung fuzzy LOPCOW, VIKOR
Biswas et al. (2022)	Dividend pay capability comparison of firms	LOPCOW, EDAS, Borda Count, Copeland, SAW, MABAC, COPRAS
Niu et al. (2022)	Site selection	Fermatean Cubic LOPCOW, EDAS
Ecer and Pamucar (2022)	Sustainability performance analysis	LOPCOW, DOBI

The findings of the related literature can be summarized as follows: Sustainability has gained significant attention in various domains including urban transportation, particularly in terms of micro-mobility, the banking sector in developing countries, and industry 4.0-based material technology, with a specific focus on warehouse management systems (Ecer et al., 2023a; Ecer and Pamucar, 2022; Simic et al., 2023). Performance analysis, as explored by Kahreman (2023), Ersoy (2023), Demir et al. (2023) and Ecer et al. (2023b) represents another prominent application of the LOPCOW method. These studies investigate measuring economic performance in 2018 economic crisis for G20 countries, analyzing performance of Borsa İstanbul retail and trade sector firms, the utilization of open government data in G20 countries for performance analysis, and assess the precision of unmanned aerial vehicles in the Agri-Food 4.0 perspective respectively. Selection problems addressing third-party logistics provider selection under sustainability perspectives for a cake manufacturer (Nila and Roy, 2023), material selection for determining the most suitable natural fiber for buildings (Ulutaş et al., 2023) and site selection for the construction of intercity railways (Niu et al., 2022) are noteworthy real-world challenges that benefit from the LOPCOW method. The LOPCOW method is also applied in the field of financial analysis, as highlighted by (Biswas et al., 2022). Urbanism is another important research area in literature, and it may also appear for several purposes such as evaluation of livable power center cities (Keleş, 2023). These findings collectively demonstrate the attention that the LOPCOW method has garnered among scholars in their quest to address current challenges. Additionally, the LOPCOW method can be effectively integrated with other MCDM methods and offers various extensions, including neutrosophic or fuzzy approaches, etc.

2.3. Literature of the MAIRCA method

In the third subsection, the literature is reviewed in terms of MAIRCA studies. Table 3 presents the studies that applied the MAIRCA method in various fields.

When Table 3 was thoroughly investigated it became apparent that the MAIRCA method has gained popularity among scholars since 2016. The findings of related literature of the MAIRCA can be grouped as follows: Technology selection has attracted attention in studies including blockchain technology selection in the logistics industry (Görçün et al., 2023), filtration technology selection for contamination control (Fetanat and Tayebi, 2023), recommender system selection for consumer decision support systems (Bączkiewicz et al., 2021), energy storage technology selection for sustainable energy systems (Pamucar et al., 2020). As environmental concerns increase due to the climate crisis, sustainability has become another prominent research topic. Assessment of sustainability factors in biofuel industry (Hezam et al., 2023), sustainable material selection for human-powered aircraft (Ul Haq et al., 2023) and sustainable energy storage system selection in India (Narayanamoorthy et al., 2023) have been notable applications recently. The MAIRCA method has been also implemented in financial studies such as critical success factor analysis of blockchain technology for agri-food supply chain management (Yontar, 2023), macroeconomic performance analysis of various countries (Bektaş and Baykuş, 2023), selecting the most proper cryptocurrencies from the investment perspective (Ecer et al. 2022), and measuring the effect of the COVID-19 pandemic on the performance of participation banking sector (Işık, 2022). Vaccine selection for the COVID-19 pandemic (Ecer, 2022), and determining the most suitable waste treatment technology (Adar and Delice, 2019) are some of the applications in the healthcare industry. Decision makers confront some real-world problems due to the new technologies. Performance evaluation of electric vehicle batteries (Ecer, 2021) and performance analysis of suppliers in the electronics sector (Chatterjee et al., 2018) are representative studies that emerge in performance analysis. Location selection and supplier selection are another important research area in literature, and it may also appear for several purposes such as location selection for wind farms (Pamučar et al., 2017), location selection for military purposes (Gigović et al., 2016) or supplier selection for dairy products (Şahin Macit, 2023). To sum it all up, it is clear that the MAIRCA method has a vast application area. The method has been integrated with various methods such as ANP, BWM, etc. It also has various extensions that use fuzzy or neutrosophic numbers.

Table 3. MAIRCA method studies

Author(s)	*Topic*	*Method*
Görçün et al. (2023)	Blockchain technology selection	Fermatian fuzzy FUCOM, Fermatian fuzzy MAIRCA
Hezam et al. (2023)	Evaluation of sustainability factors in biofuel industry	Intuitionistic fuzzy symmetry point of Criterion, Rank-Sum-Based MAIRCA
Şahin Macit (2023)	Supplier selection	AHP, MAIRCA
Bektaş and Baykuş (2023)	Macroeconomic performance analysis of selected countries	CRITIC, MAIRCA
Ul Haq et al. (2023)	Sustainable material selection	Interval-valued neutrosophic MAIRCA
Yontar (2023)	Blockchain technology	ANP, MAIRCA
Narayanamoorthy et al. (2023)	Sustainable energy storage technology selection	LDHF SOWIA, MAIRCA
Fetanat and Tayebi (2023)	Industrial filtration technology selection	q-rung orthopair fuzzy set-based MAIRCA
Işık (2022)	Analyzing effect of the COVID-19 on the performance of participation banking sector	MEREC, PSI, MAIRCA
Ecer et al. (2022)	Analyzing investment decisions in cryptocurrencies	EDAS, MAIRCA, MARCOS
Ecer (2022)	Vaccine selection	Intuitionistic fuzzy MAIRCA
Bączkiewicz et al. (2021)	E-Commerce recommender selection	TOPSIS, COMET, COCOSO, EDAS, MAIRCA, MABAC
Ecer (2021)	Performance evaluation of electric vehicle batteries	SECA, MARCOS, MAIRCA, COCOSO, ARAS, COPRAS
Pamucar et al. (2020)	Prioritization of the energy storage technologies	Dombi weighted geometric averaging operator, MAIRCA
Adar and Delice (2019)	Healthcare waste treatment technology selection	MABAC, MAIRCA, TOPSIS, VIKOR
Chatterjee et al. (2018)	Performance analysis of suppliers	R'AMATEL, MAIRCA
Pamučar et al. (2017)	Location selection for wind farms	GIS, BWM, MAIRCA
Gigović et al. (2016)	Location selection for ammunition depots	GIS, DEMATAL, ANP, MAIRCA

Overall, the comprehensive review points out that there is a gap in the literature both in terms of application area and methodology. We hope that our study will contribute to the innovation analysis based on MCDM literature.

3. METHODOLOGY

In this study, a novel hybrid methodology has been employed to compare the innovation performance of G20 countries utilizing the MCDM approach. The methodology consists of two stages. In the first stage, criteria weights are determined with the LOPCOW method, a state-of-the-art objective criterion weighting method. This method provides a robust framework for assigning weights to the criteria based on their relative importance. Then the innovation performance scores of G20 countries are measured with the MAIRCA method. This section provides the details of MCDM methods that form the basis of the methodology in this study. The MAIRCA method is a widely recognized MCDM method that allows for a comprehensive evaluation of multiple criteria and alternatives. It provides a systematic approach to assess the innovation performance of countries based on various factors such as human capital and research, infrastructure, etc. In this section, detailed explanations of the MCDM methods that form the foundation of the methodology used in this study will be provided. These methods have been preferred based on their effectiveness in handling complex decision-making problems and their relevance to the research objective of comparing innovation performance among G20 countries.

3.1. LOPCOW method

Criteria weighting is a crucial aspect in the process of solving problems using MCDM methods. The method chosen to assign values to the criteria directly impacts the ranking of the methodology. Thus, researchers have extensively investigated this issue, as demonstrated by studies conducted by Ayan et al. (2023), Durmuş and Tayyar (2017), Keskin and Kılıç Delice (2022), and Mahmoodi et al. (2023). Hence, there are scores of weighting methods that can be grouped as objective methods and subjective methods.

In this study, the LOPCOW method has been employed to objectively assign weights to the criteria that have been proposed by Ecer and Pamucar (2022) recently. The LOPCOW method offers significant advantages, such as the ability to handle negative values in the initial decision matrix (Ecer et al., 2023a). Since negativity often arises in real-world problems, the methodology must address this issue to provide effective solutions. Additionally, the method mitigates the impact of unusual values in the dataset by employing the logarithmic operator (Ecer, et al., 2023b). It also considers whether a criterion is beneficial or cost-based and removes differences in the data set by including the percentage of the mean square of measurements to their standard deviations (Ecer and Pamucar, 2022). Furthermore, the LOPCOW method demonstrates its efficacy even when dealing with large datasets (Biswas et al., 2022). The following steps are involved in determining criteria weights using the LOPCOW method (Ecer and Pamucar, 2022):

Step 1. An initial decision matrix (X) is generated (Equation 1). This matrix consists of m alternatives and n criteria.

$$X = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ \vdots & \vdots & \vdots & \vdots \\ x_{m1} & x_{m2} & \dots & x_{mn} \end{bmatrix} \tag{1}$$

Step 2. A normalized matrix (N) is required to remove measurement differences among criteria. Consequently, the elements of X are transformed to non-dimensional values within $[0, 1]$ interval. This process is implemented whether the criterion is considered as beneficial, or cost-based. The element n_{ij} ($n_{ij} \epsilon N$) is calculated using Equation 2 or Equation 3.

$$n_{ij} = \frac{x_{ij}-x_{min}}{x_{max}-x_{min}} \quad \text{(For benefit type criteria)} \tag{2}$$

$$n_{ij} = \frac{x_{max}-x_{ij}}{x_{max}-x_{min}} \quad \text{(For cost type criteria)} \tag{3}$$

Step 3. The percentage value (PV) is calculated for each criterion. To compute PV, elements of normalized matrix N (n_{ij}), the standard deviation of the criterion (σ), and the number of alternatives (m) are required. The PV values are calculated using Equation 4.

$$PV_{ij} = \left| \ln \left(\frac{\sqrt{\frac{\sum_{i=1}^{m} n_{ij}^2}{m}}}{\sigma} \right) \times 100 \right| \tag{4}$$

Step 4. The of each criterion is calculated using the PV values. The criteria weights (w_j) are obtained using Equation 5.

$$w_j = \frac{PV_{ij}}{\sum_{i=1}^{n} PV_{ij}} \quad (5)$$

3.2. MAIRCA method

The MAIRCA method was proposed by Pamučar et al. (2014). The method originates from the idea of measurement of gaps ideal between observational ratings (Yontar, 2023). In the method, a total gap is calculated for each alternative under evaluated criteria, and the alternative that has a minimal total gap is considered as the best one among its competitors (Ul Haq et al., 2023). As Gul and Ak (2020) stated the MAIRCA method resembles the TOPSIS method with its core idea. The method obtains rankings by applying the following steps (Gigović et al., 2016):

Step 1. The initial decision matrix (X) is generated as in the LOPCOW method.

Step 2. The alternative selection probability is determined. In fact, it is assumed that the decision-maker gives equal probability to select the alternatives. Thus, preference whatsoever alternative among all the alternatives is as follows (Equation 6):

$$P_{A_i} = \frac{1}{m} \quad (6)$$

Here, m is the number of alternatives and $\sum_{i=1}^{m} P_{A_i}$ equals to 1. This issue means the decision maker is neutral and the preference probability of each alternative is equal (Equation 7).

$$P_{A_1} = P_{A_2} = \cdots = P_{A_m} \quad (7)$$

Step 3. The theoretical (ideal) evaluation matrix T_p is generated (Equation 8). Elements of T_p is obtained with a multiplication of P_{A_i} and criteria weights w_j ($j = 1,2, \ldots, n$). As stated in Step 2 all P_{A_i} values are equal, T_p can written as in Equation 9.

$$T_p = \begin{bmatrix} t_{p11} & \cdots & t_{p1n} \\ \vdots & \ddots & \vdots \\ t_{pm1} & \cdots & t_{pmn} \end{bmatrix} = \begin{bmatrix} P_{A_1}w_1 & P_{A_1}w_2 & \cdots & P_{A_1}w_n \\ P_{A_2}w_1 & P_{A_2}w_2 & \ldots & P_{A_2}w_n \\ \vdots & \vdots & \vdots & \vdots \\ P_{A_m}w_1 & P_{A_m}w_2 & \cdots & P_{A_m}w_n \end{bmatrix} \quad (8)$$

$$T_p = [P_{A_i}w_1 \quad \ldots \quad P_{A_i}w_n] \quad (9)$$

Step 4. Real evaluation (observational) matrix T_r is generated (Equation 10).

$$T_r = \begin{bmatrix} t_{r11} & \cdots & t_{r1n} \\ \vdots & \ddots & \vdots \\ t_{rm1} & \cdots & t_{rmn} \end{bmatrix} \quad (10)$$

The elements of T_r (t_{rij}) is calculated considering the criterion as beneficial, or cost-based. The elements are obtained by multiplying the elements of T_p and initial decision matrix X. The element t_{rij} ($t_{rij} \epsilon T_r$) is calculated using Equation 11 or Equation 12.

$$t_{rij} = t_{pij}\left(\frac{x_{ij}-x_i^-}{x_i^+-x_i^-}\right) \quad \text{(For benefit type criteria)} \quad (11)$$

$$t_{rij} = t_{pij}\left(\frac{x_{ij}-x_i^+}{x_i^--x_i^+}\right) \quad \text{(For cost type criteria)} \quad (12)$$

Here, x_i^- and x_i^+ are elements of X. x_i^- means the minimum value of relevant criterion and x_i^+ means the maximum value of the relevant criterion.

Step 5. The total gap matrix G is generated (Equation 13). Elements of G (g_{ij}) are obtained with the subtraction of T_p and T_r.

$$G = T_p - T_r = \begin{bmatrix} g_{11} & \cdots & g_{1n} \\ \vdots & \ddots & \vdots \\ g_{m1} & \cdots & g_{mn} \end{bmatrix} = \begin{bmatrix} tp_{11} - tr_{11} & \cdots & tp_{1n} - tr_{1n} \\ \vdots & \ddots & \vdots \\ tp_{m1} - t_{m1} & \cdots & tp_{mn} - tr_{mn} \end{bmatrix} \quad (13)$$

The value of g_{ij} should equal zero or ($tp_{ij} - tr_{ij}$). Due to g_{ij} means gap if the value of g_{ij} equal to zero, it makes alternative i under the criterion j makes ideal. Or, if the value of g_{ij} equal to tp_{ij}, it makes alternative i under the criterion j makes anti-ideal.

Step 6. The criteria function (Q_i) are calculated for alternatives using their gaps. The calculation of each Q_i is given in Equation 14.

$$Q_i = \sum_{j=1}^{n} g_{ij}, i = 1,2, \ldots, m \quad (14)$$

Once the criteria functions are obtained, the scores are ranked from smallest to largest. The alternative with the smaller value has a better position in the ranking.

4. NUMERICAL IMPLICATION

This study aims to assess and compare the innovation performance of G20 countries. The analysis covers the period between 2018 and 2022. Considering the COVID-19 pandemic outbreak in 2019, it will be possible to monitor changes in the innovation performance of countries. Thus, the analysis also helps to reveal the significant changes in innovation performance in the long term. The related data was gathered from the Global Innovation Index 2018 (Cornell University et al., 2018), 2019 (Cornell University et al., 2019), 2020 (Cornell University et al., 2020), 2021 (WIPO, 2021), and 2022 (WIPO, 2022) reports. The countries included in the analysis are as follows: Argentina, France, Japan, South Africa, Australia, Germany, Mexico, Türkiye, Brazil, India, South Korea, United Kingdom, Canada, Indonesia, Russia, United States, China, Italy, and Saudi Arabia. It also should be noted that the European Union was excluded from the context of the study though it is a member of G20 due to it is a political and economic union rather than a country.

The explanation of each criterion included in the analysis is as follows (WIPO, 2022):

- Institutions (C_1) pertains to the political, regulatory, and business environments.
- Human capital and research (C_2) involve education, tertiary education, research, and development (R&D).
- Infrastructure (C_3) takes into consideration information and communication technologies (ICTs), general infrastructure, and ecological sustainability.
- Market sophistication (C_4) considers aspects such as credit, investment, trade, diversification, and market scale.
- Business sophistication (C_5) addresses knowledge workers, innovation linkages, and knowledge absorption.
- Knowledge and technology outputs (C_6) focus on knowledge creation, knowledge impact, and knowledge diffusion.
- Creative outputs (C_7) encompass intangible assets, creative goods, and services, and online creativity.

The reason for preferring the LOPCOW and MAIRCA methods should be clarified. Although there is no rule of thumb for selecting the most appropriate MCDM method for any problem, the reason to prefer them would better to be underlined. The objectivity of these methods and the absence of their integration in the literature are the main reasons. Furthermore, the ability to reduce the effect of unusual values in the data set and the fact that it works effectively with large data sets are important factors in choosing the LOPCOW method. Whereas MAIRCA was preferred because of its similarity to TOPSIS which is one of the cornerstones among MCDM methods.

In the calculations, it is assumed that all criteria are of the benefit type, since the higher the values of all these criteria, the better for the relevant alternative. After determining the type of criterion, the innovation performance of countries was analyzed with a four-stage approach. In the first stage criteria weights were calculated using the LOPCOW method. The obtained criteria weights were used in the second stage with the MAIRCA method. In the third stage, a sensitivity analysis was performed to test the robustness of the approach. In the fourth and final stage, a comparative analysis was conducted with MARCOS, TOPSIS, MABAC, and EDAS methods to validate the approach adopted in this study. The mentioned stages applied in this study are illustrated comprehensively in Figure 1. It should be noted that the results of the computational steps could not be included due to the word limit in the paper.

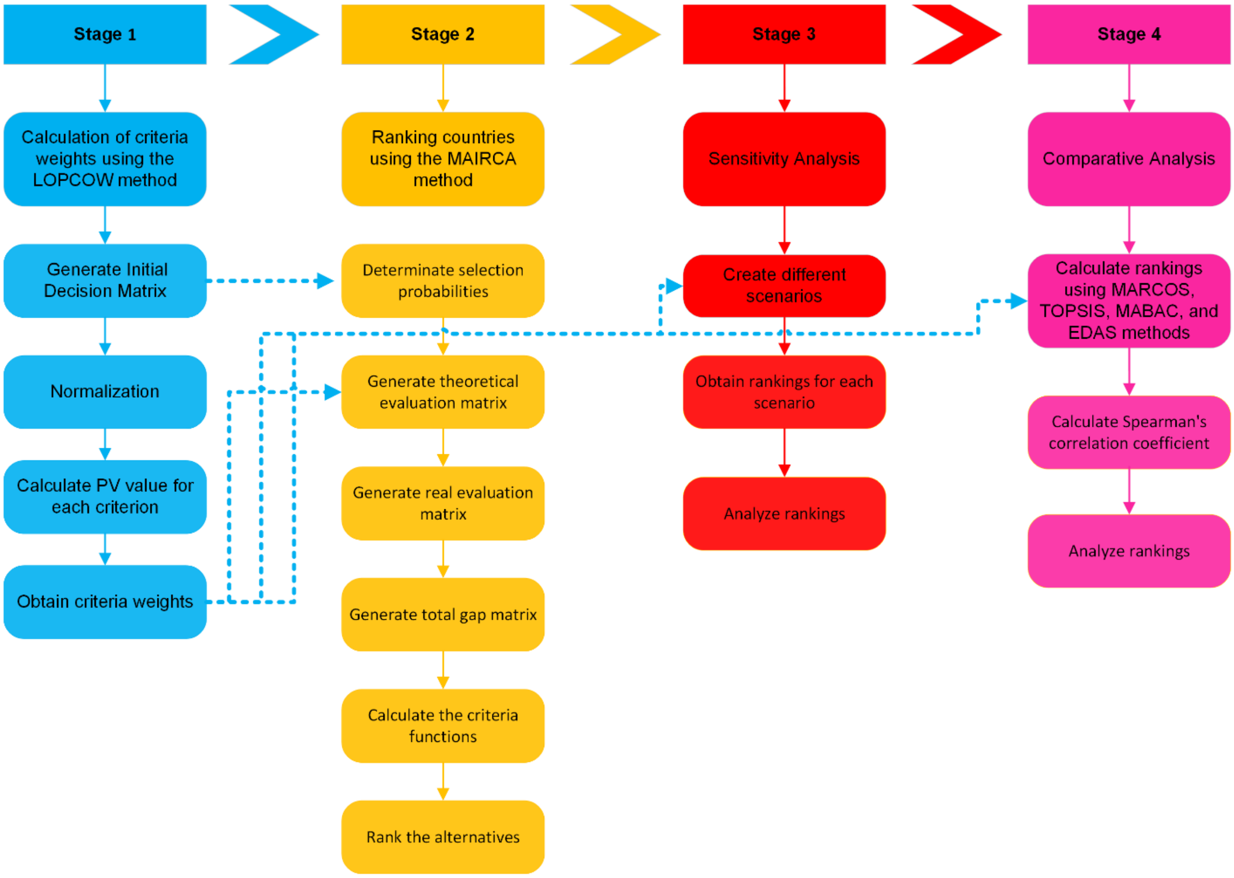

Figure 1. Flow chart of the LOPCOW-MAIRCA method

Stage 1. Determination of criteria weights: The criteria weights were calculated using the LOPCOW method. To determine the criteria weights, Equations (1) to (5) were applied. Since the analysis covers a five-year period between 2018 and 2022, each year has unique data, criteria weights were calculated for each year which makes it possible. This approach allows for monitoring significant changes in criteria weights on a yearly basis. The results of the criteria weight calculations are presented in Table 4.

Table 4. Criteria weights by year

Year	C_1	C_2	C_3	C_4	C_5	C_6	C_7
2018	0.1126	0.1948	0.1456	**0.1620**	0.1487	0.1232	0.1132
2019	0.1266	**0.1919**	0.1512	0.1573	0.1378	0.1172	0.1180
2020	0.1264	**0.1828**	0.1198	0.1791	0.1582	0.1278	0.1059
2021	0.1301	0.1601	**0.1722**	0.1507	0.1192	0.1347	0.1330
2022	0.1176	**0.1807**	0.1340	0.1806	0.1486	0.1155	0.1230
Average	0.1227	**0.1821**	0.1446	0.1659	0.1425	0.1237	0.1186

Table 4 indicates that Human capital and research (C_2) is consistently the most important criterion for the years 2019, 2020, and 2021, and the average. Market sophistication (C_4) takes precedence as the most important criterion for the year 2018. Similarly, Infrastructure (C_3) holds the highest importance for the year 2021. None of the other criteria were determined as the most important in any year. It is noteworthy that Institutions (C_1) had the least significance in 2018, Business sophistication (C_5) in 2021, Knowledge and technology outputs (C_6) in 2019 and 2022, and Creative outputs (C_7) in 2020 and on average. Moreover, Human capital and research (C_2) has gained increasing importance since the onset of the pandemic. For a more detailed visual representation, refer to Figure 2.

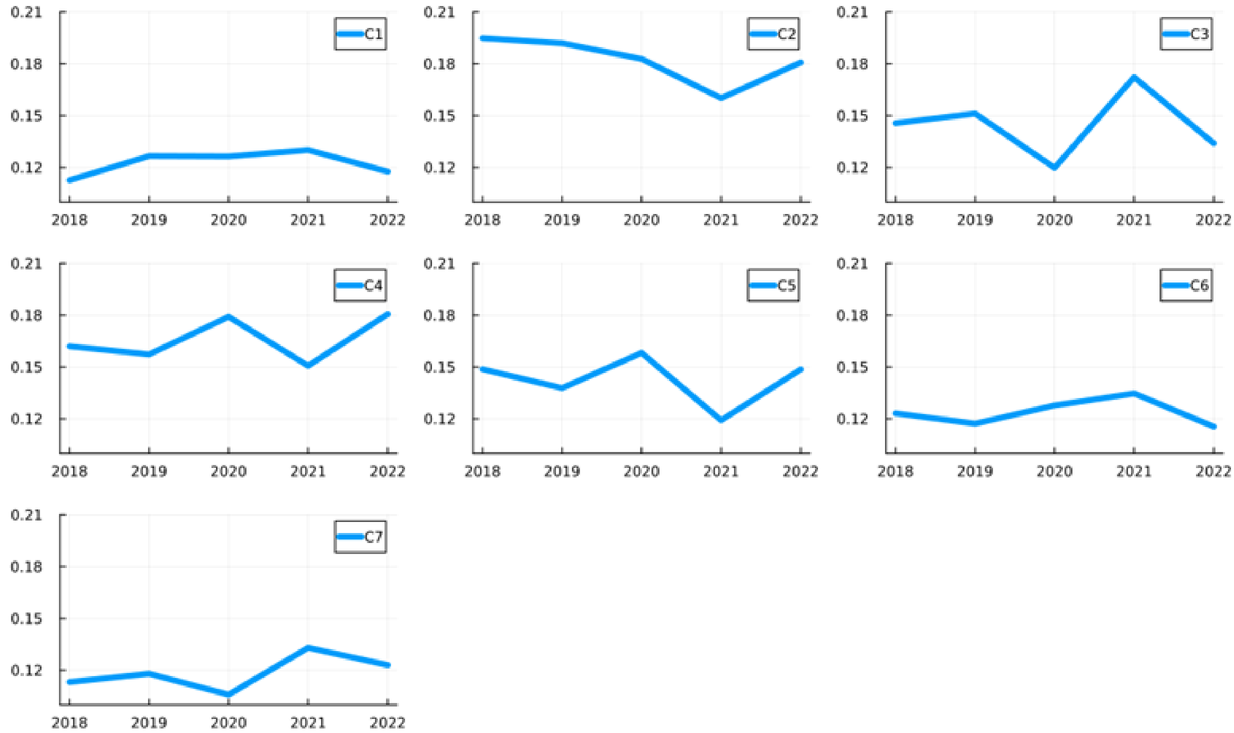

Figure 2. Breakdown of criteria weights changes

The changes in criteria weights can be easily observed with the assistance of Figure 2. The figure presents information about each criterion for each year. The figure allows for the confirmation of trends, as well as the identification of minimum and maximum values. For example, C_1 (Institutions) does not exhibit a distinct trend, but the minimum value of the criterion was recorded in 2018, likewise, the maximum value was observed in 2021. Similar observations can be made from Figure 2 regarding other criteria. As of 2020, Infrastructure (C_3) and Creative outputs (C_7) are seen as criteria with increased importance due to the COVID-19 pandemic. This can be considered as a suggestion to investors and policymakers. It would be appropriate to direct more investments to criteria whose importance level has increased with COVID-19.

Stage 2. Ranking countries using the MAIRCA method: In the second stage, the MAIRCA method was employed to rank the G20 countries. The method utilizes Equations (6)-(14) to determine the rankings. The criteria weights obtained in the first stage were utilized in the calculation of the theoretical evaluation matrix T_p. The criteria function, which assesses the total gap between alternatives and the ranking of countries, is provided in Table 5.

Based on the data presented in Table 5, The United States has consistently held the top position for the past four years. The United Kingdom, which held the first position in 2018, dropped to the second position and has maintained that rank ever since. Germany and South Korea have consistently vied for the third and fourth positions in the ranking, demonstrating a similar level of competitiveness. Moreover, Indonesia has consistently shown the poorest performance among the countries throughout most of the years. An illustrative plot would facilitate a clear understanding of the performance changes among the countries.

Upon analyzing Figure 3, it can be inferred that several countries, such as the United States, United Kingdom, Germany, South Korea, Argentina, and Indonesia, have experienced minimal changes in their performance over time, often gaining or losing just one position in the ranking. Italy has consistently maintained its position in the ranking throughout the entire period. On the other hand, countries like South Africa, Saudi Arabia, Brazil, Russia, Canada, and Japan have exhibited inconsistent performance in the ranking, showing fluctuations over time. Furthermore, it is noteworthy to mention Türkiye's performance. Türkiye’s initially held the 13^{th} position in the ranking but has progressively improved its performance over time, attributed to its investments in innovation.

Table 5. Rankings based on the MAIRCA method

	LOPCOW-MAIRCA									
	2018		*2019*		*2020*		*2021*		*2022*	
Country	*Score*	*Ranking*	*Score*	*Ranking*	*Score*	*Ranking*	*Score*	*Ranking*	*Score*	*Ranking*
Argentina	0.0462	18	0.0440	18	0.0459	18	0.0526	**19**	0.0470	18
Australia	0.0139	7	0.0164	8	0.0160	8	0.0139	9	0.0184	9
Brazil	0.0420	16	0.0415	16	0.0405	17	0.0313	14	0.0418	15
Canada	0.0141	8	0.0139	6	0.0125	5	0.0100	6	0.0149	7
China	0.0188	9	0.0181	9	0.0177	9	0.0130	8	0.0150	8
France	0.0134	6	0.0140	7	0.0134	7	0.0105	7	0.0127	5
Germany	0.0110	3	0.0101	3	0.0107	4	0.0087	4	0.0112	4
India	0.0426	17	0.0409	15	0.0382	13	0.0306	13	0.0377	13
Indonesia	0.0501	**19**	0.0487	**19**	0.0494	**19**	0.0385	18	0.0474	**19**
Italy	0.0253	10	0.0253	10	0.0244	10	0.0198	10	0.0260	10
Japan	0.0119	5	0.0133	5	0.0128	6	0.0098	5	0.0134	6
Mexico	0.0409	14	0.0400	13	0.0397	16	0.0316	15	0.0445	16
South Korea	0.0114	4	0.0108	4	0.0093	3	0.0064	3	0.0105	3
Russia	0.0358	11	0.0359	11	0.0355	11	0.0285	12	0.0390	14
Saudi Arabia	0.0388	12	0.0403	14	0.0395	15	0.0322	16	0.0369	12
South Africa	0.0413	15	0.0424	17	0.0393	14	0.0325	17	0.0461	17
Türkiye	0.0397	13	0.0381	12	0.0371	12	0.0270	11	0.0364	11
United Kingdom	0.0063	**1**	0.0064	2	0.0062	2	0.0054	2	0.0076	2
United States	0.0077	2	0.0059	**1**	0.0045	**1**	0.0043	**1**	0.0041	**1**

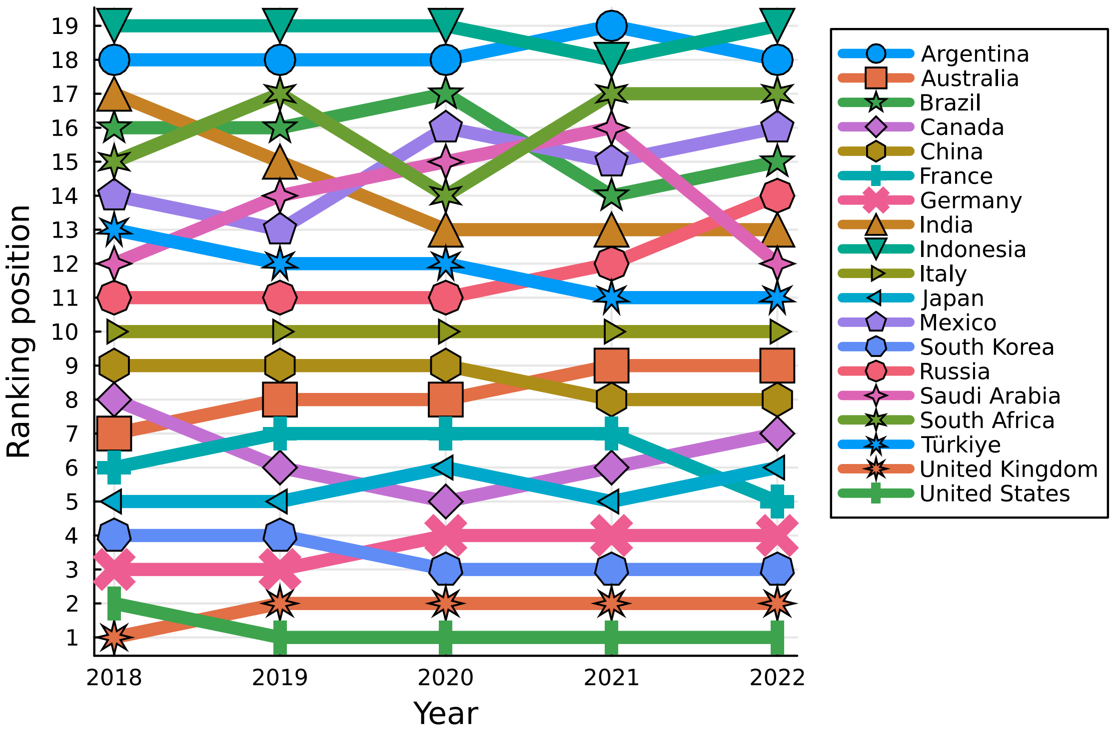

Figure 3. Country ranking changes as a result of the LOPCOW-MAIRCA methodology

When the innovation performance of countries as of COVID-19 is analyzed, we see those 6 countries (United States, United Kingdom, South Korea, Germany, Italy, and India) have maintained their place in the ranking. In addition to these countries, 5 countries (France, China, Türkiye, Saudi Arabia, and Brazil) have improved their performance until 2022. 4 countries (Japan, Mexico, Indonesia, and Argentina) returned to their performance in 2020, albeit with a change in 2021. Canada, Australia, Russia, South Africa, Russia, South Africa are seen as countries with deteriorating innovation performance. Overall, in total, 14 countries either maintained their position, improved, or returned to their previous performance in the following year after the outbreak of the COVID-19 pandemic. These findings are in line with the interpretation of Jewell (2019) mentioned in the introduction. In other words, the expectation that investments in innovation would decrease due to the COVID-19 was not met and investments continued to increase. Therefore, it can be interpreted that through innovation investments the negative effects of COVID-19 were eliminated in the innovation performances of countries.

Stage 3. Sensitivity analysis: The changes in the parameters of MCDM approaches may have an enormous effect on the rankings. Sensitivity analysis helps researchers to detect the robustness of their adopted methodologies. To conduct a sensitivity analysis, some scenarios were generated and tested in this study. Furthermore, the sensitivity analysis specifically focuses on the year 2022, allowing for insights based on the most current period. The generated scenarios and relevant criteria weights are provided in Table 6.

Table 6. Criteria weights by scenarios

Scenario	w_1	w_2	w_3	w_4	w_5	w_6	w_7
Scenario 1	0.1176	0.1807	0.1340	0.1806	0.1486	0.1155	0.1230
Scenario 2	0.1429	0.1429	0.1429	0.1429	0.1429	0.1429	0.1429
Scenario 3	0.1230	0.1155	0.1486	0.1806	0.1340	0.1807	0.1176
Scenario 4	0.1250	0.2500	0.1250	0.1250	0.1250	0.1250	0.1250
Scenario 5	0.1250	0.1250	0.1250	0.1250	0.1250	0.2500	0.1250

Scenario 1 represents the criteria weights obtained using the LOPCOW method for the year 2022. Scenario 2 involves assigning equal weights to all criteria. Scenario 3 is the reverse of Scenario 1, where the weights are flipped. Scenario 4 assigns a weight of 0.25 to the most important criterion of Scenario 1 and 0.125 to the rest. Similarly, Scenario 5 assigns a weight of 0.25 to the least important criterion of Scenario 1 and 0.125 to the rest. The results of the LOPCOW-MAIRCA approach using these criteria weights in the respective scenarios are visualized in Figure 4.

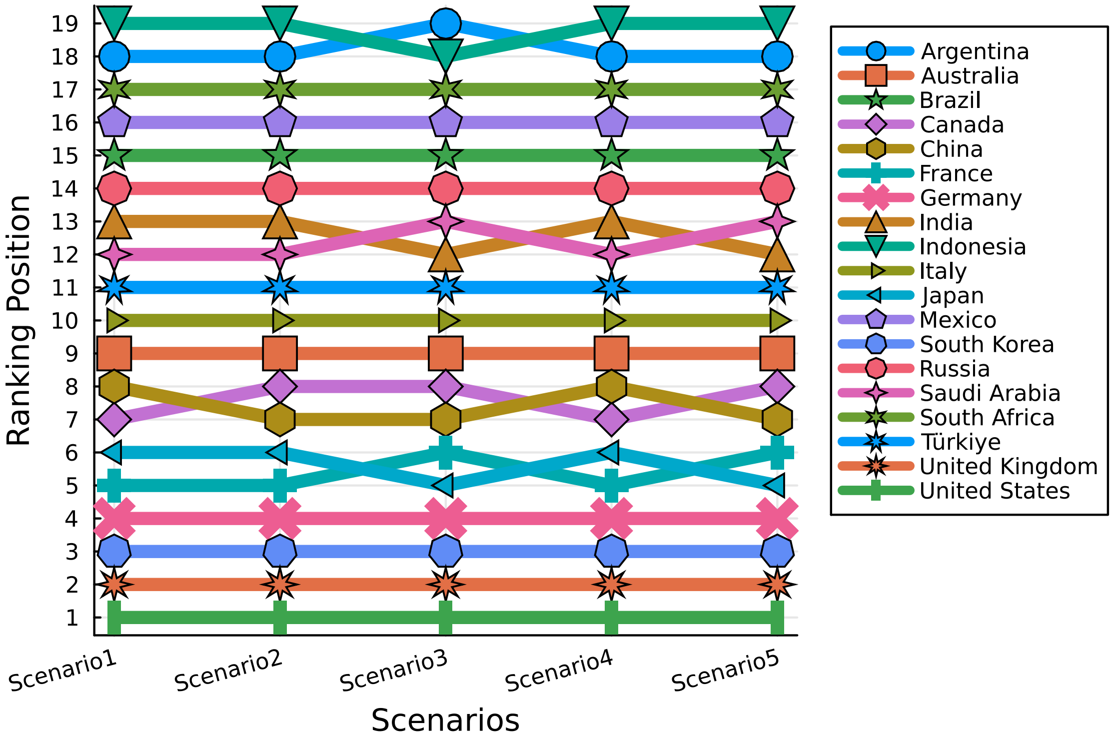

Figure 4. Sensitivity analysis results

After analyzing Figure 4, it can be concluded that the LOPCOW-MAIRCA approach consistently produces robust ranking results. Out of the 19 countries, 11 of them maintained their positions in the ranking across all scenarios. The remaining countries showed minor variations, with only a one-position difference in the overall ranking. These findings indicate that the methodology is not significantly influenced by changes in criteria weights.

Stage 4. Comparative analysis: To investigate the results of an MCDM approach is essential in terms of validating and ensuring the reliability of the rankings. Conducting a comparative analysis is a common practice among researchers to address validation and reliability issues, as this helps prevent potentially misleading results. In this study, the LOPCOW-MAIRCA approach is compared with other prominent methods in the MCDM literature, namely MARCOS, TOPSIS, MABAC, and EDAS methods. Since there is no widely accepted metric in the field of MCDM to measure the relative performance of methods, these types of comparisons between methods are often employed. When choosing the methods for comparison, selecting those with similar principles makes it easier to illustrate how well the results of the proposed methodology align with the outcomes of other methodologies.

The analysis was carried out using the same set of criteria weights for all methods, which were obtained using the LOPCOW method. The comparative analysis focuses on the year 2022 like the sensitivity analysis. The results of all the methods are presented in Table 7.

Based on the data presented in Table 7, it is evident that the United States and the United Kingdom consistently occupy the top two positions across all the methods. Similar rankings can also be observed for other countries such as Australia, Brazil, and South Africa. Notably, the rankings obtained from LOPCOW-MAIRCA, LOPCOW-MARCOS, and LOPCOW-MABAC methods are identical, indicating a high degree of agreement among these approaches. Furthermore, Spearman's rank correlation between LOPCOW-MAIRCA and LOPCOW-TOPSIS is found to be 0.98, while the correlation between LOPCOW-MAIRCA and LOPCOW-EDAS is 0.99. These high correlation values suggest a strong consistency between the rankings produced by the LOPCOW-MAIRCA approach and the other methods. These findings support the assertion made by Ecer (2022) that the LOPCOW-MAIRCA approach yields reliable and valuable results similar to those obtained by other approaches.

Table 7. Results of the comparative analysis

Country	*LOPCOW-MAIRCA*	*LOPCOW - MARCOS*	*LOPCOW - TOPSIS*	*LOPCOW -MABAC*	*LOPCOW - EDAS*
Argentina	18	18	19	18	18
Australia	9	9	9	9	9
Brazil	15	15	15	15	15
Canada	7	8	8	7	8
China	8	7	6	8	6
France	5	5	4	5	5
Germany	4	4	3	4	4
India	13	12	11	13	12
Indonesia	19	19	18	19	19
Italy	10	10	10	10	10
Japan	6	6	7	6	7
Mexico	16	16	16	16	16
South Korea	3	3	5	3	3
Russia	14	14	14	14	14
Saudi Arabia	12	13	13	12	13
South Africa	17	17	17	17	17
Türkiye	11	11	12	11	11
United Kingdom	2	2	2	2	2
United States	**1**	**1**	**1**	**1**	**1**

5. DISCUSSION

This study analyzed the innovation performance of G20 countries in the period covering 2018-2022. According to the findings, in 2018, Infrastructure (C_3) was determined as the most important criterion. In the subsequent years of 2019, 2020, and 2022, Human capital and research (C_2) took precedence, indicating a shift in focus toward education and R&D. Similarly, in 2021, Market sophistication (C_4) emerged as the criterion with the highest importance. When analyzing the changes in the most important criteria over time, it is evident that the emphasis has shifted from infrastructure to education and R&D. These criteria collectively contribute to a country's innovation capabilities, and it is reasonable for their priorities to change over time. As one factor reaches its saturation point, another factor becomes prominent in attracting investments and driving societal transformation. Factors such as new technologies, the impact of the COVID-19 pandemic, and the ongoing process of digital transformation shape the global landscape. The ranking of countries in terms of innovation is not an ultimate and definitive representation. Conversely, the proposed approach should be considered as an alternative method that encompasses the diverse aspects of innovation. However, through the proposed methodology, some outcomes can be provided. In light of the findings obtained in our study, we can say that the continuation of innovation investments despite the COVID-19 pandemic has positive effects on the innovation performance of countries. However, each country will be able to decide which sub-dimension of innovation to invest in with priority using the approach we proposed in this study. Consequently, countries should prioritize education and R&D activities to foster an innovative ecosystem. When shifting the focus from criteria to alternatives, it is expected that developed countries would demonstrate superior performance compared to their less-developed counterparts. The findings confirm this expectation, as the United States, the United Kingdom, Germany, and South Korea showcase the most successful innovation performance within the scope of this analysis. Economic and technological advantages provide these countries with a conducive environment for innovation. Furthermore, the findings of the study confirm that as long as investment in innovation continues, countries' innovation performance will not be affected by universal catastrophic events such as COVID-19.

It is important to support the findings of our study with the findings of other studies in literature. Studies on innovation performance in literature are discussed in the literature section. However, it is not possible to make a detailed comparison due to the differences in the scope (countries, periods, approaches) of these studies. Nevertheless, when the findings of the study by Ecer and Aycin (2023) are analyzed, it is seen that the innovation performances of the US and UK countries are in parallel with the results of our study and that they are in the first two places in both studies.

6. CONCLUSION

A novel integrated MCDM approach was proposed to assess and compare comprehensively the innovation performance of G20 countries. The proposed approach comprises four stages. In the first stage, the LOPCOW method procured needed criteria weights in an objective way. Also, this method is one of the state-of-the-art MCDM methods that doesn't require individual evaluations of the decision maker(s). The countries were ranked using the MAIRCA method in the second stage. The final two stages were conducted to test the robustness, reliability, and validation of the proposed approach. To achieve this, prominent MCDM methods, namely TOPSIS, MARCOS, MABAC, and EDAS were involved in a detailed comparative analysis. The susceptibility to criteria weight changes was also analyzed under five different scenarios. Moreover, the analysis conducted in this study is comprehensive both in terms of the methodology employed and the period of the analysis. The study covers a five-year period, allowing for the monitoring of the impact of the pandemic on innovation performance. The adopted approach in this study is expected to make a valuable contribution to the literature in the mentioned aspects.

As in every scientific study, there are some limitations in this study. Since the data used in the study are available at the end of annual reporting periods, it is not possible to analyze countries in narrower time windows (monthly, quarterly, semi-annually). Moreover, the importance levels of the criteria included in the analysis were obtained using the information contained in the data set. The fact that the assessments of experts in the field are not included in the calculation of these importance levels can be interpreted as a limitation. Finally, since the innovation performance rankings of countries are obtained only in line with the content of the data set, different findings may emerge from this study using different data sets.

In further studies, there is potential to broaden the scope by including countries from different regions around the world. Additionally, apart from the information provided in the dataset, incorporating the expertise of innovation experts could enhance the analysis process. This could be achieved by utilizing different weighting methods or MCDM methods that incorporate extensions of uncertainty theories. By incorporating these elements, the assessment of innovation performance can be further refined and provide more comprehensive insights.

Author Contributions

Tayfun Öztaş: Literature Review, Methodology, Modelling, Analysis, Writing-original draft, Writing-review, and editing. *Gülin Zeynep Öztaş*: Literature Review, Conceptualization, Writing-original draft, Writing-review, and editing

Conflict of Interest

No potential conflict of interest was declared by the authors.

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Compliance with Ethical Standards
It was declared by the authors that the tools and methods used in the study do not require the permission of the Ethics Committee.

Ethical Statement
It was declared by the authors that scientific and ethical principles have been followed in this study and all the sources used have been properly cited.

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