Journal of Computer Science and Electrical Engineering
Print ISSN: 2663-1938
Online ISSN: 2663-1946
DOI: https://doi.org/10.61784/jcsee3089

AHP-TOPSIS-BASED ASSESSMENT FRAMEWORK FOR CYBERSECURITY POLICY EFFECTIVENESS: EMPIRICAL EVIDENCE FROM GCI INDICATORS

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Abstract: With the acceleration of global digitalization, cybercrime has exhibited transnational and covert characteristics, posing severe challenges to national cybersecurity. To scientifically evaluate the cybersecurity level of various countries and identify effective policy pathways, this study proposes a comprehensive evaluation model integrating the Analytic Hierarchy Process and Technique for Order Preference by Similarity to Ideal Solution. Based on the five pillars of the International Telecommunication Union Global Cybersecurity Index, an evaluation system comprising 15 sub-indicators is constructed. Indicator weights are determined through expert scoring, and the TOPSIS algorithm is employed to conduct quantitative ranking and grading of the cybersecurity levels of 27 countries. The results show that there is a significant positive correlation between cybersecurity level and comprehensive national strength. Technologically advanced countries such as Finland and the United States are rated as "Excellent", while less developed countries such as Zimbabwe fall into the "Weak" category. Furthermore, Pearson correlation analysis on U.S. cybercrime data and demographic characteristics reveals that internet usage, employment to population ratio of men aged 15-24 and GDP exhibit significant statistical associations with cybercrime incidence. This study provides a data-driven decision-making framework for policymakers to optimize cybersecurity strategies and verifies the core role of synergistic governance of law and technology.
Keywords: AHP-TOPSIS; National cybersecurity level assessment; GCI; Cybercrime prevention and control

1 INTRODUCTION

In recent years, the rapid development of information technology has profoundly promoted global connectivity. While significantly enhancing social productivity, it has also amplified cybersecurity risks. Cyber threats exhibit strong transnationality and concealment. To address systemic risks, countries around the world are actively formulating cybersecurity strategies. Therefore, constructing a scientific and quantifiable national cybersecurity level assessment system is of great significance for identifying weak links, optimizing resource allocation, and improving global cyber resilience. This study intends to integrate the Analytic Hierarchy Process (AHP) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) to establish a comprehensive evaluation model. In existing studies, Ashour M and Mahdiyar A pointed out that the application of the AHP method in multi-criteria decision-making has been continuously expanding, with significant advantages especially in risk assessment and resource allocation, however, current research has paid insufficient attention to the complex and multi-dimensional field of cybersecurity, and its applicability in dynamic cyber threat environments remains to be improved [1]. To this end, Alhakami combined fuzzy AHP with TOPSIS to construct a comprehensive assessment framework, which was used to evaluate the effectiveness of intrusion detection methods under Gen V multi-vector attacks [2]. Nevertheless, Wang et al. argued that although AHP and TOPSIS perform well in determining indicator weights, existing studies have not fully explored the impact of multi-source information such as expert trust information and corporate preference information on assessment accuracy [3]. In addition, Yu proposed a cybersecurity situation assessment method based on a fusion model, which improved the quality and efficiency of feature extraction but failed to fully cover the specific cybersecurity needs of the Industrial Internet of Things (IIoT) [4]. This paper proposes a new model combining AHP and TOPSIS methods, which aims to provide comprehensive support for the scientific assessment of national cybersecurity levels.

The main contributions of this paper include: 1) Developed a comprehensive evaluation model based on AHP-TOPSIS, realizing the quantitative assessment of national cybersecurity levels. 2) Innovatively deconstructs the five pillars of the Global Cybersecurity Index (GCI) into 15 sub-indicators and resolves the coupling among the indicators through the AHP. 3) Revealed multidimensional correlations between cybercrime and demographic characteristics through Pearson correlation analysis, providing empirical evidence for targeted policy formulation.

The structure of this paper is as follows: The first part is the introduction, which introduces the research background, current research status, and contribution points; The second part is related theories, which expounds on AHP, TOPSIS and Pearson; The third part is model establishment and analysis, which describes in detail the model ideas and establishment process; The fourth part is model conclusions, which summarizes the research results; The fifth part is the conclusion, which expounds on the research significance and future prospects.

2 RELATED THEORIES

The AHP is a systematic decision-making method. It decomposes complex problems into multiple levels and factors, then conducts pairwise comparisons of these factors through expert judgments to construct a judgment matrix, thereby determining the weights of each factor and ultimately providing decision support. The core of the AHP algorithm lies in integrating qualitative analysis with quantitative analysis: through a hierarchical structure, it breaks down complex decision-making problems into multiple comparable subproblems, and determines the relative importance of each factor based on expert experience [5]. This method is particularly applicable to decision-making problems that are difficult to directly subject to quantitative analysis, such as evaluating the relative importance of different threat factors in cybersecurity risk assessment [6].

The TOPSIS algorithm is a commonly used multi-criteria decision analysis method. Its core idea is to construct the ideal solution and the negative ideal solution, then calculate the distances between each alternative and the ideal solution as well as the negative ideal solution, and determine the ranking of each alternative in terms of superiority or inferiority based on these distances. The basic steps of the TOPSIS algorithm include: constructing the decision matrix, normalizing the decision matrix, determining the ideal solution and the negative ideal solution, calculating the distances between each alternative and the ideal solution as well as the negative ideal solution, calculating the relative closeness of each alternative, and finally ranking the alternatives based on the relative closeness [5].The TOPSIS algorithm boasts advantages such as clear conceptualization, simplicity in calculation, and effectiveness in handling multi-criteria decision-making problems. In the field of network security, this algorithm can be applied to evaluate the effectiveness of different security solutions. For instance, it enables the selection of the optimal security solution by considering multiple indicators of security schemes, including cost, performance, and reliability [7].

The Pearson correlation coefficient (PCC) is a commonly used statistical measure of the linear relationship between two variables. Its core concept is to quantify the strength of the positive or negative change in one variable when the other variable changes. It determines the correlation by calculating the ratio of the covariance between two variables to the product of their standard deviations. The result ranges from -1 to +1, where +1 indicates perfect positive linear correlation, -1 indicates perfect negative linear correlation, and 0 indicates no linear correlation [8-10]. The Pearson correlation coefficient has a wide range of applications, playing a significant role not only in basic statistical analysis but also being integrated into various complex decision-making, prediction, and machine learning models [11-14].

3 EXPERMENTS

National cybersecurity level is related to multiple factors. Given the existence of assessment tools such as the International Telecommunication Union (ITU)'s GCI, we adopted the five indicators and 15 sub-indicators from this research to construct a national cybersecurity level evaluation index system [15]. Based on this information, we ultimately employed a combined method of AHP and TOPSIS to evaluate a country's cybersecurity level. When analyzing complex decision-making problems, the AHP decomposes the problem into different levels, including the goal layer, criterion layer, and alternative layer. Subsequently, a judgment matrix is constructed by comparing the relative importance of elements within the same level, and the weights of each element are calculated. Finally, ranking and decision-making are performed based on the weights and the scores of the alternative layer.

Constructing the judgment matrix: By reviewing relevant literature, this study obtained expert ratings for the five indicators in the main criterion layer. The rating result for each indicator is the average of the expert ratings, from which the final ratings are derived [16], and then the judgment matrix is determined as shown in Table 1. Among them, F1: Legal, F2: Technical, F3: Organizational, F4: Capacity development, F5: Cooperation.

Table 1 AHP Judgment Matrix of Main Criteria Layer Based on Expert Ratings

	F1	F2	F3	F4	F5
F1	1	9	2	8	6
F2	1/9	1	1/6	1/2	1/3
F3	1/2	6	1	3	2
F4	1/8	2	1/3	1	1/2
F5	1/6	3	1/2	2	1

Calculation of eigenvectors:For the judgment matrix R , compute its largest eigenvalue. Eigenvector v is a nonzero vector satisfying the following equation:

$$Rv=\lambda v \tag{1}$$

The eigenvalues are obtained by solving the characteristic equations:

$$det(R-\lambda I)=0 \tag{2}$$

For each eigenvalue λ,substituting into the matrix equation:

$$(R-\lambda I)v=0 \tag{3}$$

By solving this system of linear equations,we obtain the corresponding eigenvectors v. Normalize the feature vectors so that the weights sum to 1:

$$w=\frac{v}{\sum_{i=1}^{n} v_i} \tag{4}$$

Calculate Consistency Ratio: Calculation of consistency indicators CI the formula is as follows

$$CI=\frac{\lambda_{max}-n}{n-1} \tag{5}$$

Next, the consistency ratio is calculated, with its formula as follows:

$$CR=\frac{CI}{RI} \tag{6}$$

If CR<0.1 then the consistency of the judgment matrix is better. If CR > 0.1 then the judgment matrix needs to be readjusted.The calculated CR value is 0.998, which proves that the consistency of the judgment matrix is acceptable.

For the word criterion layers S1, S2, S3 ......S15, we use the same method to figure out their weights.The weights of the criterion and sub-criterion layers are used to obtain the combined weights of the factors. For a given criterion , its final weight is:

$$w(C_k)=\sum_{i=1}^{m_k} w(C_k,S_i)\times w(S_i) \tag{7}$$

The TOPSIS algorithm is then used to score and rank each country [17]. For each country, normalize the ratings in each sub-criterion by dividing the rating by the maximum value of that sub-criterion across all countries:

$$X_{ij}=\frac{x_{ij}}{max(x_{ij})} \tag{8}$$

Apply the aggregated weights of the sub-criteria to the normalized decision matrix:

$$V_{ij}=X_{ij}\times w_j \tag{9}$$

Determine the ideal and anti-ideal solutions:

$$A^{+}=\left(max\left(V_{ij}\right)\right) \tag{10}$$

$$A^{-}=\left(min\left(V_{ij}\right)\right) \tag{11}$$

Compute the Euclidean distance of each country from the ideal and anti-ideal solutions:

$$D_i^{+}=\sqrt{\sum_{j=1}^{m}\left(V_{ij}-A_j^{+}\right)^2} \tag{12}$$

$$D_i^{-}=\sqrt{\sum_{j=1}^{m}\left(V_{ij}-A_j^{-}\right)^2} \tag{13}$$

Calculate the relative closeness of each country to the ideal solution:

$$C_i=\frac{D_i^{-}}{D_i^{+}+D_i^{-}} \tag{14}$$

Next, this study analysed the correlation between cybercrime and demographic data in the United States between 2000 and 2022. Since demographic characteristics have many kinds, so we firstly choose many kinds of demographic characteristics data, and based on the number of cybercrimes under different years, we conduct Spearman correlation analysis on them. Since the crime situation in the United States is characterized by a large amount of data and volatility relative to the crime situation in other countries, and the number of crimes in other countries is often in a state of zero relatively over a period of time, which is not conducive to data analysis, we have chosen the U.S. data for correlation analysis here.

This study uses Pearson's product-moment correlation coefficient to quantify the linear correlation between demographic indicators and cybercrime rates. For a bivariate dataset containing n=23 observations, the correlation coefficient r is calculated using the following formula:

$$r_{XY}=\frac{\sum_{i=1}^{n}(X_i-\bar{X})(Y_i-\bar{Y})}{\sqrt{\sum_{i=1}^{n}(X_i-\bar{X})^2}\sqrt{\sum_{i=1}^{n}(Y_i-\bar{Y})^2}} \tag{15}$$

To test the statistical significance of r, construct the t-statistic:

$$t=r\sqrt{\frac{n-2}{1-r^2}}\sim\ t(n-2) \tag{16}$$

4 RESULTS

This study employs the AHP-TOPSIS model to evaluate the cybersecurity levels of 27 countries, with its key findings manifested in two dimensions:

Characteristics of indicator weight distribution: The weights of the five pillars determined by the model via the AHP algorithm show significant differences (Figure 1). The legal dimension dominates absolutely with a weight of 52.32%, among which personal data protection (PP, 33.14%) and effective data protection regulations (DPF, 13.63%) are key sub-indicators. The technical dimension has the lowest weight (4.33%), with the adoption of cybersecurity standard frameworks (FCS, 0.42%) among its sub-indicators showing a weak contribution. The organizational (24.17%), cooperative (11.9%), and capacity-building (7.28%) dimensions together form a secondary support layer. This weight distribution indicates that cybersecurity levels are mainly driven by legal completeness, with the marginal utility of technical means being limited.

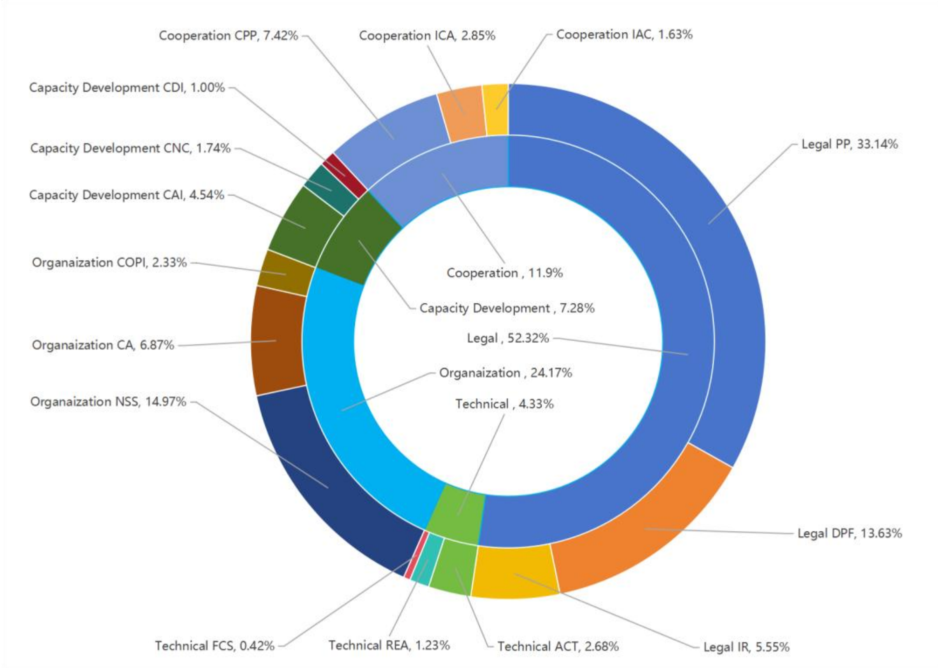

Figure 1 Indicator Weights

Polarization of national scoring grades: The ranking of Ci values based on the TOPSIS algorithm (Figure 2) reveals a polarization in the cybersecurity levels of the 27 countries: High-score group (Ci≥0.8): 13 countries including Finland (0.91), the United States (0.89), and Singapore (0.87), with their legal dimension scores all exceeding 0.9 (out of 1) and organizational dimension scores >0.85; Low-score group (Ci≤0.2): 10 countries including Zimbabwe (0.15), Niger (0.17), and Equatorial Guinea (0.18), with their legal dimension scores all below 0.2 and technical dimension scores less than 0.1.

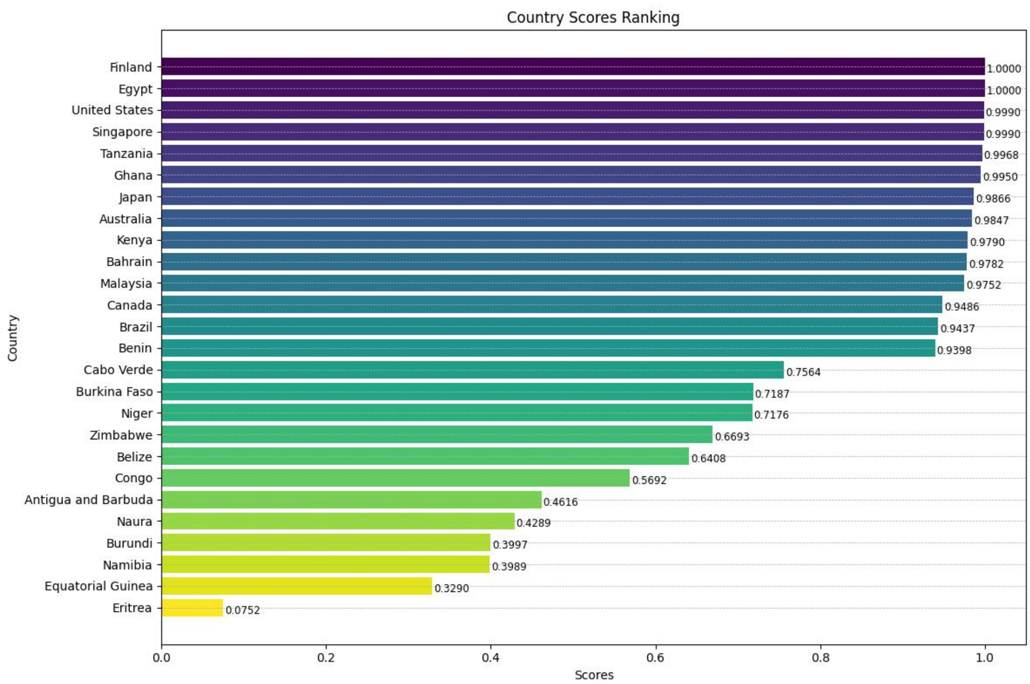

Figure 2 Score Ranking

The heat map of Pearson's correlation analysis is shown in Figure 3, and some demographic characteristics t-test results are shown in Table 2. The result revealed that a statistically robust negative correlation between youth employment rates (aged 15–24) and cybercrime incidence, where higher workforce engagement correlates with reduced criminal activity. Concurrently, internet usage exhibits a strong positive association, confirming that expanded digital access inherently broadens attack surfaces. Gross Domestic Product demonstrates a paradoxical role: while economic advancement enables technological resilience, it simultaneously elevates cyber-risk exposure through increased digitalization. Critically, these demographic and economic dynamics are subordinate to legal infrastructure—which holds 52.32% weight in our AHP-TOPSIS framework—as evidenced by nations like Finland maintaining low cybercrime despite high internet/GDP metrics through stringent data protection laws (PP: 33.14% sub-weight). Other variables, including inflation and educational attainment, lack significant explanatory power. Thus, effective cybersecurity policy must prioritize youth employment stabilization and calibrated digital inclusion, all anchored by legislative rigor.

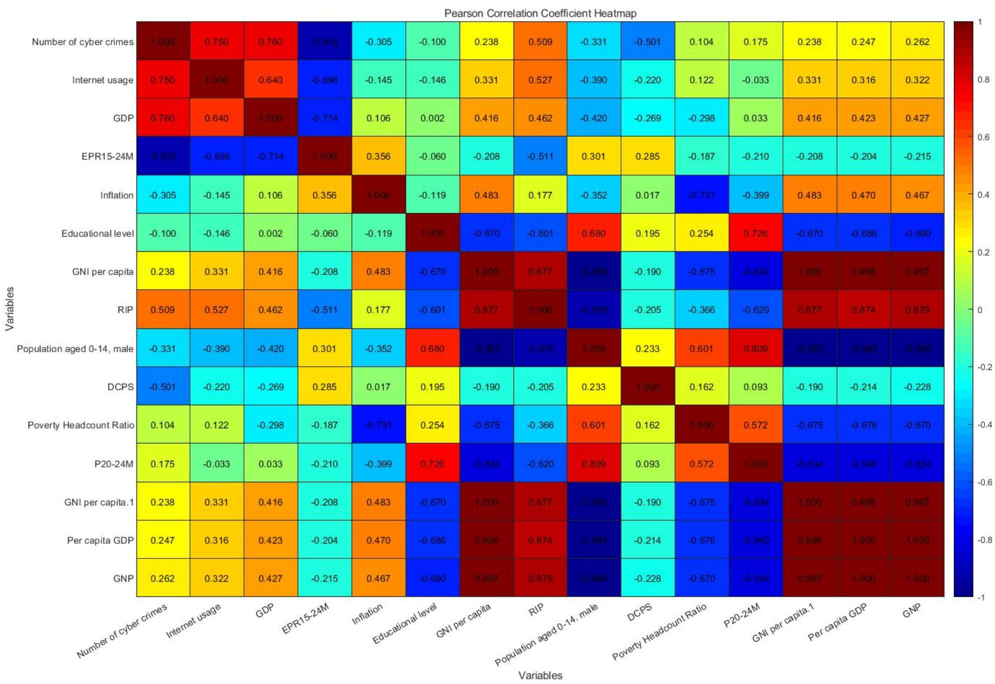

Figure 3 Pearson Correlation Analysis Heat Map

Table 2 Some Demographic Characteristics t-Test Results

Variable	r	t	Significance level
EPR15-24M	-0.912	-10.19	1%
Internet usage	0.750	5.20	1%
GDP	0.760	5.36	1%
Inflation	-0.305	-1.47	Not significant
Educational level	-0.100	-0.46	Not significant

5 CONCLUSIONS

This study innovatively constructs an AHP-TOPSIS comprehensive evaluation model to achieve a quantitative assessment of national cybersecurity levels, effectively addressing the shortcomings of existing research in adapting to multi-dimensional complex cybersecurity environments. The model is based on the five pillars of the International Telecommunication Union's Global Cybersecurity Index, innovatively decomposing them into 15 sub-indicators. Expert scores were used to determine the weights, and the TOPSIS algorithm was applied to rank and classify the cybersecurity levels of 27 countries. The results indicate that cybersecurity levels are significantly positively correlated with a country's overall strength, with the legal dimension accounting for over half of the weighting, making it the core factor influencing cybersecurity, while the marginal utility of technical measures is relatively limited. Further Pearson correlation analysis reveals that factors such as youth employment rates, internet usage rates, and GDP are significantly associated with cybercrime rates in the United States. This study not only provides data-driven decision support for policymakers but also validates the critical role of legal and technical collaborative governance in cybersecurity. Future research could consider incorporating more country samples and dynamic indicators to further optimize the timeliness and applicability of the evaluation system.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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