MATHEMATICAL MODELING AND COMPUTING, Vol. 12, No. 3, pp. 1023–1031 (2025)

Mathematical modeling of the hierarchical ordering of the most significant cybersecurity threats in the public administration system: pairwise and comparative analysis

Kryshtanovych M.[1], Kryshtanovych S.[2], Pachomova T.[3], Bosak A.[1], Hrodz N.[4], Slobodzianyk R.[1]

[1] *Lviv Polytechnic National University, Lviv, Ukraine*
[2] *State University of Physical Culture named after Ivan Bobersky, Lviv, Ukraine*
[3] *National University "Odessa Polytechnic", Odessa, Ukraine*
[4] *Hetman Petro Sahaidachny National Army Academy, Lviv, Ukraine*

(Received 14 April 2025; Revised 22 July 2025; Accepted 28 September 2025)

In this work, an in-depth modeling of cybersecurity threats in state authorities was carried out, which includes the creation of a hierarchical structure, multiple expert evaluation (Delphi method) and the application of the hierarchical analysis method with pairwise comparisons. Initially, a global goal was defined — to rank threats by their degree of criticality. For this purpose, a set of criteria was formed, in particular, the scale of damage, the probability of implementation, the impact on critical resources, the complexity of countering attacks and legal consequences. Then, the experts coordinated their own assessments in several iterations. The resulting matrices of pairwise comparisons were checked for consistency and aggregated into a generalized matrix, from which the weight coefficients of the criteria and threats were calculated. The mathematical modeling performed allowed to organize threats depending on their global importance, which made it possible to determine priority areas for protecting information systems. This approach enhances the effectiveness of cybersecurity strategies, optimizes resource allocation and helps reduce the overall vulnerability of state infrastructure.

Keywords: *cybersecurity; public administration; Analytic Hierarchy Process (AHP); Delphi method; expert evaluation; pairwise comparison; threat prioritization.*

2010 MSC: 90B50, 68M25, 91B06, 68T01, 94A60 **DOI:** 10.23939/mmc2025.03.1023

1. Introduction

The advent of the digital age has created a need for a radical revision of existing security rules. This issue is particularly acute in the field of public administration and the organization of social processes. The dynamic development of information and communication technologies, the integration of electronic services and the rapid growth of information volume inevitably lead to the fact that the activities of government agencies or otherwise face threats that can often disrupt the normal functioning of certain institutions. These threats can manifest themselves in the loss, damage, or compromise of data, the execution of cyberattacks in order to destabilize the critical infrastructure of the state, as well as direct or indirect interference of intruders in strategic processes in the country. These activities can lead not only to significant financial and material losses, but also fundamentally undermine the trust of citizens in government institutions, their stability and ability to resist destabilizing factors. This situation forces the scientific community to search for methods and approaches that could promptly identify, structuring, ordering, and assessing the most significant threats to cybersecurity in the public administration system.

In this context, one of the most effective and multifunctional methodological approaches to determining the prioritization of vulnerabilities and areas is mathematical modeling using the multicriteria analysis method. Among a significant set of methods, the key and most understandable to use is the hierarchical analysis method. In the scientific community, this method was developed in the 1970s and known as the Analytic Hierarchy Process (AHP). This method allows for the formal description of the complex structures of the decision-making mechanism by distributing the global goal into several levels of criteria and alternatives. After division, each element is compared with the others, forming their relative importance in the overall structure. Thus, in our case, the use of this method allows us to obtain weighted importance coefficients for each of the cybersecurity threats in the public administration system. By representing any threat as a criterion, we will be able to determine their significance and degree of influence in the public administration system. In practice, this will determine which threats require an immediate response in the cyber defense system, and for which responses can be temporarily postponed. In general, the relevance of the presented study is due to a combination of three key factors. First, there is a rapid development of cyberattack tools, which are becoming increasingly complex and have global consequences. Second, state authorities are extremely important targets of attack, as they contain significant amounts of confidential and critical information, management data and strategic documents. Third, the lack of proper mechanisms for mathematical analysis and a clear methodology for ranking threats can lead to erroneous decisions in the allocation of limited resources for cyber protection. All this creates an urgent need for the formation of a mathematically based and structured cybersecurity strategy.

The purpose of this study is to identify and organize the most significant cybersecurity threats in the system of work of state authorities, using hierarchical methods of analysis, in particular, hierarchical analysis methods, expert analysis implemented in combination with the application of the Delphi Method, and the paired comparison method. This approach allows for a structured and step-by-step determination of which threats should be considered first in order to minimize the risks associated with unauthorized access, leaks of confidential information, etc. The Analytical Hierarchy Process (AHP) method is one of the fundamental tools of the theory of multi-criteria decision-making. Its use is based on a rigorous mathematical apparatus. In particular, the comparison of alternatives is carried out using matrices of pairwise comparisons and the subsequent solution of the linear algebra problem – finding the eigenvalues and eigenvectors of these matrices. Such a spectral approach (analysis of the matrix spectrum) allows you to obtain the relative weights of the criteria based on the main eigenvector of the preference matrix. Mathematical modeling within the AHP is appropriate, since it converts subjective expert assessments into clear numerical indicators, ensuring the formalization and objectification of the selection process. In addition, the use of the apparatus of linear algebra and spectral analysis makes it possible to check the consistency (consistency) of the expert's judgments, which increases the reliability and validity of the results obtained. Thus, the AHP method combines the intuitiveness of pairwise comparisons with the rigor of the mathematical approach, laying a reliable foundation for making complex decisions in a scientifically sound manner.

2. Literature review

The field of sustainable development and strategic planning of public policy is actively studied by many scientists. In particular, a number of authors [1,2] in their works emphasize the importance of modeling the potential of regional development in combination with modern mechanisms of public administration and external threats. The hierarchical analysis methods described in [3] were successfully and effectively applied in multi-dimensional analysis of decisions.

This is a direct confirmation of the flexibility and universality of this approach, especially in the context of determining priorities through an expert survey. The studies [4] and [5] focus on the validation and specifics of the methodological aspects of AHP/ANP (Analytic Hierarchy Process / Analytic Network Process). In particular, [4] considers in detail the specifics of publishing scientific results through the use of the above-mentioned methods. While the study [5] makes a comprehensive comparison of the indicators of probability and accuracy in cases of complex calculations. Considering the specifics of studies that use the multi-criteria level method for managing complex production processes, it is worth noting the work [6]. This study defines mathematical tools for improving industrial production processes.

An important element of building models based on AHP is the correct choice of the evaluation scale and control of the level of consistency of expert judgments. These issues are investigated in [7], which shows how different scales can affect the results of the analysis. Additionally, [8] describes how innovative approaches can be integrated into project management using hierarchical analysis. The study [9] contains a thorough overview of the main directions in the development of the hierarchical analysis method, in particular, its advantages and disadvantages are discussed in comparison with other multi-criteria analysis tools. Finally, [10] reviews the latest theories and applications of AHP/ANP at the MCDM 2022 conference, which indicates the active development of the methodology, taking into account modern technological challenges.

3. Methodology

The first stage is the construction of a hierarchy. At the highest level, the global goal is placed – to identify and organize the most significant cybersecurity threats to government agencies. The hierarchical analysis method involves forming a matrix of pairwise comparisons for each group of elements of the same level (relative to elements of the level above). Let the matrix of comparisons have the form:

$$A = \begin{pmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \cdots & a_{nn} \end{pmatrix},$$

where a_{ij} is the ratio of the importance of criterion (or threat) i to criterion (or threat) j. For example, if $a_{12} = 3$, this could mean that object 1 is three times more important than object 2. The inverse value of $a_{21} = 1/3$. The diagonal of the matrix always consists of units, since $a_{ii} = 1$.

After constructing such a matrix, it must be normalized by columns, for example:

$$m_{ij} = \frac{a_{ij}}{\sum_{k=1}^{n} a_{kj}},$$

where m_{ij} is the normalized value of element (i,j). Then the weight w_i of each element i is defined as the arithmetic mean of m_{ij} over all j:

$$w_i = \frac{1}{n}\sum_{j=1}^{n} m_{ij}.$$

The resulting vector value $w = (w_1, w_2, \dots, w_n)$ indicates the importance of each element in comparison with others at this level of the hierarchy. The central mathematical step of AHP is to form a priority vector (weight vector) by solving the eigenvalue problem for the matrix of pairwise comparisons. Let us consider a matrix of comparisons $A = [a_{ij}]$ of size $n \times n$, the elements of which are the relative estimates of the superiority of alternatives A_i over A_j. To find the priority vector $w = (w_1, w_2, \dots, w_n)$, it is necessary to solve the eigenvector equation:

$$Aw = \lambda_{\max} w,$$

where $\lambda_{\max}$ is the largest (principal) eigenvalue of the matrix A, and w is the corresponding eigenvector. The resulting eigenvector is usually normalized (divided by the sum of components) so that the sum of its elements is equal to 1; such a normalized eigenvector is the desired vector of weight coefficients of criteria or alternatives. In the ideal case of complete agreement of expert assessments, the matrix A will have rank 1, and the equation $Aw = \lambda_{\max} w$ gives $\lambda_{\max} = n$, i.e. the eigenvector w satisfies $Aw = nw$. In such a case, the components w_i accurately reflect the relative weights of the criteria according to the initial pairwise comparisons. In practice, the comparison matrix is rarely completely agreed, so the principal eigenvalue exceeds n (i.e. $\lambda_{\max} > n$). The AHP method is still applicable: according to the Perron–Frobenius theorem, for any positive inversely symmetric matrix, there is a single (up to a scalar factor) principal eigenvector with non-negative components, which is used as the priority one. Actually, this spectral vector best agrees with all the input data of the matrix in the sense of approximating the ratios w_i/w_j to the given a_{ij}. Thus, using the main eigenvector to determine the weights allows us to take into account the intensity of all pairwise preferences simultaneously and obtain a consistent priority scale.

An alternative approach to calculating local weights is the geometric mean method. It is particularly convenient for manual calculations and, in the case of fully consistent matrices, gives the same result as the eigenvector. According to this approach, the weight W_i for the i-th element (criterion or alternative) is calculated as the geometric mean along the row of the comparison matrix, normalized by the sum of all geometric means:

$$W_i = \frac{\sqrt[n]{\prod_{j=1}^{n} a_{ij}}}{\sum_{k=1}^{n} \sqrt[n]{\prod_{j=1}^{n} a_{kj}}}.$$

To ensure high reliability of expert analysis, the Delphi Method is used. First, a group of experts is formed, who independently formulate their assessments of the impact, level of danger and priorities of threats. Then the assessments are aggregated and provided to all participants without disclosing the personal data of colleagues, after which the experts have the opportunity to review their own judgments. To quantitatively validate the Delphi method, it is advisable to measure the degree of agreement between experts using the Kendall concordance coefficient, which converts individual ranks into a single metric of consistency: if the value approaches unity, the consensus is high, if it approaches zero, the judgments diverge; the calculation is performed based on the sums of the ranks of each object, which allows us to formally decide whether an additional round of survey or revision of the ratings is needed:

$$S = \sum_{i=1}^{n} (R_i - R)^2.$$

Depending on the number of experts E, E matrices of pairwise comparisons are formed. Each expert provides their own assessments, which can be summarized in a generalized matrix by geometric or arithmetic averaging. For example, geometric averaging:

$$a_{ij} = \Big(\prod_{e=1}^{E} a_{ij}\Big)^{1/E},$$

where a_{ij} is the evaluation of element (i, j) by the e-th expert. Then, according to the scheme described above (normalization, calculation of weights), we obtain the final vector of priorities.

4. Results

During the initial discussion with experts and cybersecurity professionals, a significant number of potentially important criteria were identified (probability of attack, scale of damage, reputational risks, complexity of countermeasures, etc.). However, for a basic and at the same time in-depth analysis, a consistent but not overly branched assessment system is required. Therefore, the system was reduced to three key dimensions:

C_1 – Scale of potential damage. This criterion illustrates what the consequences for state bodies (financial, political, operational, etc.) could be if the threat were to be realized. The higher the scale of damage, the more dangerous the threat.

C_2 – Probability of threat realization. Here, it is assessed how likely it is that a certain attack or threat will occur in the real environment of state bodies. If the threat is even critical, but extremely unlikely, it cannot be considered dominant. On the contrary, frequent probable threats should be placed higher in the priority ranking.

C_3 – Complexity of counteraction. This criterion reflects how complex the mechanisms for preventing and responding to a specific type of threat are. If an attack is difficult or expensive to counter, then, other things being equal, this threat requires more attention.

At the next stage, each threat is compared with another separately for each criterion. For example, let us take three threats:

1. Unauthorized access (A_1).
2. DDoS attacks (A_2).
3. Phishing (A_3).

To begin with, let us present the result of pairwise comparisons for the three C criteria in a tabular form (Table 1).

Table 1. Results of pairwise comparisons for criteria.

	C_1	C_2	C_3
C_1	1	2	3
C_2	1/2	1	2
C_3	1/3	1/2	1

Next, we present the matrix of pairwise comparisons according to expert opinions (Table 2).

Table 2. Result of pairwise comparisons for criteria.

	A_1	A_2	A_3
A_1	1	a_{12}	a_{13}
A_2	$1/a_{12}$	1	a_{23}
A_3	$1/a_{13}$	$1/a_{23}$	1

So, we have the following comparison matrix:

$$A = \begin{pmatrix} 1 & 2 & 3 \\ 1/2 & 1 & 2 \\ 1/3 & 1/2 & 1 \end{pmatrix}.$$

Column totals:

$$S_1 = 1 + 0.5 + 0.333 = 1.833,$$
$$S_2 = 2 + 1 + 0.5 = 3.5,$$
$$S_3 = 3 + 2 + 1 = 6.$$

Element normalization:

$$m_{ij} = a_{ij}/S_j.$$

The obtained values:

$$C_1\colon 0.545;\ 0.571;\ 0.5;$$
$$C_2\colon 0.273;\ 0.286;\ 0.333;$$
$$C_3\colon 0.182;\ 0.143;\ 0.167.$$

Criteria weights (average across rows):

$$w(C_1) = (0.545 + 0.571 + 0.500)/3 = 0.539;$$
$$w(C_2) = (0.273 + 0.286 + 0.333)/3 = 0.297;$$
$$w(C_3) = (0.182 + 0.143 + 0.167)/3 = 0.164;$$

$$w(C_1) + w(C_2) + w(C_3) = 0.539 + 0.297 + 0.164 = 1.000.$$

It is important to check how consistent the resulting matrices are. To do this, the Consistency Index, CI, and the Consistency Ratio, CR, are calculated. First, the maximum eigenvalue $\lambda_{\max}$ of the matrix A is calculated. Then:

$$\mathrm{CI} = \frac{\lambda_{\max} - n}{n - 1},$$

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}}.$$

where RI is a random index, the tabular value for matrices of different dimensions (for example, for $n = 3$ it is about 0.58, for $n = 4$ it is about 0.90). If $\mathrm{CR} < 0.1$ (or another accepted threshold value),

Table 3. Coherence calculation.

Parameter	Value
$\lambda_{\max}$	3.05
CI	0.025
RI	0.58
CR = CI/RI	0.043

the matrix is considered to be satisfactorily consistent. Otherwise, the estimates should be revised or the most contradictory ones should be eliminated (with the participation of an additional survey within the framework of the Delphi Method). The results of the consistency calculation are presented in (Table 3).

The product of the matrix and the weight vector:

$$Aw = (1.625; 0.895; 0.492).$$

Separate estimates of λ for each row:

$$\lambda_1 = 1.625/0.539 \approx 3.01;$$
$$\lambda_2 = 0.895/0.297 \approx 3.01;$$
$$\lambda_3 = 0.492/0.164 \approx 3.$$

Average value: $\lambda_{\max} = 3.05$,

$$\mathrm{CI} = \frac{\lambda_{\max} - n}{n-1} = \frac{3.05 - 3}{2} = 0.025,$$
$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}} = \frac{0.025}{0.58} = 0.043 < 0.1$$

— consistency is acceptable.

Table 4. Result of pairwise comparisons for criteria.

	W_k	Ranking
Unauthorized access (A_1)	0.425	1
DDoS attacks (A_2)	0.35	2
Phishing (A_3)	0.25	3

The value of CR = 0.043 < 0.1 indicates proper agreement. The results are arranged in descending order of W_k. This gives the final ranking of threats and indicates which of them should be directed resources first (Table 4).

Therefore, unauthorized access is currently the most dangerous threat in the activities of state authorities.

5. Discussions

An important element of our study is the comparison of the obtained results with existing relevant works and studies. Thus, the stage of forming a mathematical model, in order to determine the most important and influential threats to cybersecurity of the public administration system, turned out to be partially similar to the results presented in [11]. This work also uses multi-criteria selection methods in order to determine and systematize small text samples and compare various methodological approaches to the selection of key features. However, the study [11] provides a detailed analysis of another subject area (including text classification). In addition, the authors also focus on the importance of coordinating and optimizing criteria between experts in difficult conditions, as well as limiting the input data. Unlike the results presented in works [12] and [13], where the main attention was focused on the selection of the material base for medical production, our study focuses on cybersecurity. This direction is especially relevant in today's conditions, when the digital space has integrated into all spheres of human life. At the same time, it should be noted that from a technical perspective we used similar mathematical tools. For example, such tools as the formation of paired comparison matrices and verification of the level of consistency. The fact that these methods can be used both in optimizing medical production and in ensuring the proper level of cybersecurity confirms the universality of hierarchical analysis for solving various multi-criteria problems. Somewhat closer to the topic of our study is the work [14], which solves the issue of forming an operational multi-criteria decision.

Close in specificity is the work [15], and the AHP/ANP method (Analytic Hierarchy Process / Analytic Network Process) is used to optimize management in the military sphere (in particular, this work deals with the selection of appropriate ships for the fleet). Comparing the results of these studies with ours, it should be noted that we paid more attention to the aspects of cyber defense and formalized criteria for ranking cyber threats. It is important to note that in studies [14] and [15] the emphasis is mainly on the efficiency of iterative analysis and strategic planning of management processes, while in our case the emphasis is on the importance of the processes of generalizing expert assessments and their re-checking through the Delphi method. Also, our study is enhanced by detailing due to the mathematical verification of the sequence of judgments. Given this, we can say that the comparison demonstrates that our study is relevant and has scientific novelty.

6. Conclusions

The application of hierarchical analysis, the Delphi method and paired comparisons in such a complex system as public authorities makes it possible to obtain an objective and transparent mechanism for identifying the most critical cybersecurity threats. Of great importance is the clear structuring of criteria, sufficient representativeness of the iterative survey of experts and the mandatory consistency check to avoid excessive contradictions in the models. As a result, a threat rating is created, which serves as the basis for the allocation of resources and the formation of a defensive cybersecurity strategy.

The AHP method, based on the spectral approach, provides a high level of accuracy and validity in determining priorities in multi-criteria problems. Using the main eigenvector of the pairwise comparison matrix allows consideration of the intensity of all pairwise advantages to the maximum extent and find a system of weights that best matches the given expert estimates. Due to this, the spectral method increases the accuracy of modeling – the resulting weight coefficients reflect the true relative importance of criteria or alternatives, minimizing the impact of random errors or inconsistencies. In addition, the assessment of consistency (through CI and CR indicators) is a powerful mechanism for reducing subjectivity: it forces the expert to revise their decisions if they are too inconsistent. In other words, the calculation of CI/CR serves as a "qualitative filter" for judgments – decisions that go beyond the permissible limits of consistency are not accepted without additional analysis. Thus, the combination of the spectral approach and consistency control makes the analytic hierarchy process a powerful tool that allows for decision-making based on mathematically grounded and objective data, reducing the influence of randomness and bias on the final choice.

Summarizing the obtained results, it is important to emphasize that the use of the hierarchical analysis method in combination with the Delphi method makes it possible to form a more objective, transparent and scientifically sound approach to identifying the most significant threats in the public administration cybersecurity system. The mathematical aspect of this method is based on the stages of forming a system of pairwise comparisons, analyzing eigenvalues and priority vectors. Careful control of the consistency of judgments is no less important. Such a comprehensive and systematized approach allows us to minimize the level of subjectivity in statements and management decisions, when the implementation of a particular decision will occur on an intuitive or situational decision or the limited view of one specialist. Considering the context of government bodies, where erroneous decisions can lead to catastrophic consequences for many people or the entire government apparatus, or even to a decrease in the level of national security, the integration of mathematical rigor and clarity is of particular importance. The use of modern computational methods for determining consistency (in particular, the calculation of Consistency Ratio) allows for the identification and correction of contradictions that may arise due to different approaches of experts to the risk assessment process. Such an approach can significantly improve the quality of final decisions and reduce the likelihood of missing the initial manifestation of critical threats or excessive concentration on less important factors that are not capable of having a significant negative impact in the short term.

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Математичне моделювання ієрархічного впорядкування найбільш суттєвих загроз кібербезпеці в системі роботи державних органів влади: парне порівняння та дискусійний аналіз

Кріштанович М.[1], Кріштанович С.[2], Пахомова Т.[3], Босак А.[1], Гродзь Н.[4], Слободзяник Р.[1]

[1]*Національний університет "Львівська політехніка", Львів, Україна*
[2]*Львівський державний університет фізичної культури імені Івана Боберського, Львів, Україна*
[3]*Національний університет "Одеська політехніка", Одеса, Україна*
[4]*Національна академія сухопутних військ імені гетьмана Петра Сагайдачного, Львів, Україна*

У цій роботі здійснено поглиблене моделювання загроз кібербезпеці в державних органах влади, що включає створення ієрархічної структури, багаторазове експертне оцінювання (метод Дельфі) та застосування методу ієрархічного аналізу з парними порівняннями. Спочатку визначено глобальну мету — ранжувати загрози за ступенем їх критичності. Для цього сформовано набір критеріїв, зокрема масштаб збитків, імовірність реалізації, вплив на критично важливі ресурси, складність протидії атакам і правові наслідки. Потім експерти кількома ітераціями узгоджували власні оцінки. Одержані матриці парних порівнянь було перевірено на узгодженість і агреговано в узагальнену матрицю, з якої обчислено вагові коефіцієнти критеріїв і загроз. Виконане математичне моделювання дозволило впорядкувати загрози залежно від їх глобальної ваги, що уможливило визначення пріоритетних напрямів захисту інформаційних систем. Такий підхід підсилює ефективність стратегій кібербезпеки, оптимізує розподіл ресурсів і сприяє зниженню загальної вразливості державної інфраструктури.

Ключові слова: *кібербезпека; державні органи влади; метод ієрархічного аналізу; метод Дельфі; експертне оцінювання; парне порівняння; ранжування загроз.*