Risk-based decision-making: extended F-Entropy method with correction factor based 2D-FAHP method

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Abstract. In complex decision-making processes using multi-criteria decision-making methods, experts' beliefs and judgments, as well as their knowledge, are influential in the comparisons between criteria and alternatives, which may lead to overlapping importance rankings of criteria. In this study, to increase the degree of representativeness of uncertainties in overlapping criteria evaluations, a correction term is integrated into the fuzzy entropy method, so that the risk cost levels of the main criteria of equal importance differ according to the number of sub-criteria. The integrated correction term into the fuzzy entropy calculation is proposed as a relative importance weight multiplier in the two-dimensional fuzzy AHP process steps. Although the α-alpha truncation method is proposed for the Fuzzy AHP method, the decision matrix is converted into crisp values in the process stages and directly reduced to the Classical AHP method. Within this article, using the judgment matrix with interval values is proposed instead of exact judgment values as to not distort the fuzzy structure of the result values. In the article, the two-dimensional fuzzy Entropy weights obtained by using the alpha-cutting method can be used as a relative importance weight multiplier in the fuzzy AHP process proposed in two dimensions to obtain clear importance rankings of the criteria. Thanks to the method approach proposed, OCTAVE Allegro logic is combined to create a relative risk matrix according to the risk environment conditions for the criteria alongside the ranking level.

Keywords: Fuzzy entropy, Fuzzy AHP, Decision-Making, Two-Dimensional FAHP

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1. Introduction

Digital information assets are the data, documents, and systems in electronic media that organizations create, store, and manage to support decision-making processes and provide competitive advantage. These assets are exposed to various risks such as unauthorized access, disruption of data integrity, and cyber threats. Since traditional measures such as firewalls, antivirus programs and encryption are insufficient, dynamic decision-making processes including multi-criteria evaluation and risk-based approaches are needed [21]. As the need for dynamic and risk-based decision-making processes for the security of digital information assets is increasing, the basis of these processes is the identification and analysis of threats. Risk-based decision-making approaches for the protection of digital information assets identify potential threats, systematically analyze their likelihood and impact, and enable effective risk management by

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ensuring that limited resources are allocated to the most critical security measures. In this context, identifying threats, examining the organizational structure, analyzing and prioritizing human interactions, relationships between subsystems and security attitudes contribute to more effective determination of security strategies. In particular, methods such as OCTAVE etc., which address the degree of risk, the probability and impact of risk factors, allow organizations to systematically assess and manage risks and create proactive decision mechanisms by continuously monitoring risk management [6]. Within this article, the risk levels of critical information assets under unstable environmental conditions will be determined within the framework of protection of digital information assets and efficient use of resources. The aim is to conduct more specific research on the use of Analytic Hierarchy Process (AHP) and entropy methods together in two-dimensional (2D) analysis and to contribute to the enrichment of literature.

Considering the time and financial constraints, the high level of risk structure and uncertainty in ensuring the confidentiality-integrity-availability of information requires the use of multi-criteria decision-making methods in establishing the framework of information security risk assessment. Classical multi-criteria decision-making methods used in decision-making theory, which are based on personal judgments alongside the handling of risks, uncertainties and complex-valued problems over a period of time, can be transformed into a flexible structure with a fuzzy logic approach because they contain imprecise information, and it is difficult to assign performance levels to criteria. Fuzzy logic approaches system behavior is used where analytical functions are unavailable. In cases where the behavior is not well understood, solutions involving complex systems can be obtained that provide fast and approximate solutions. In determining the appropriate solution structure, experts must select from a set of alternatives. In the decision process for selecting alternatives, many factors such as organizational needs, goals, risks, benefits, resources, etc. are considered. Accordingly, a systematic and objective evaluation process is needed for decision makers to determine the most appropriate alternative, and multi-criteria decision-making techniques help determine the most appropriate option among the alternatives.

The AHP method, developed for solving complex multi-criteria problems, ranks the decision options from high to low importance within the scope of the criteria determined by the decision maker(s) among multiple options [17]. AHP is based on the assumption that subjective judgments cluster decision elements according to their common characteristics and includes the preferences, knowledge and intuition of groups or individuals in the decision-making process [20]. In the decision-making process, the more information the criterion attribute provides to the decision maker, the more effective that attribute is in the decision-making process. In this context, the real weight of the criteria attributes, which are the source of information in decision-making, includes both objective and subjective judgments simultaneously. At this point, while AHP is one of the methods that commonly use subjective judgments in multi-criteria decision-making processes, the Entropy method provides objective weighting. The Entropy method, which determines criterion weights, is based on the information value and discrimination of the criteria and contributes to obtaining more rational and consistent results by providing an objective weighting in the decision process [2]. In analyzing the complexity of decision-making processes, hybrid models created by integrating multi-criteria decision-making methods with different methods increase the accuracy and efficiency of the decision-making process. Feizi et al. [7] showed that a hybrid weighting method created by integrating TOPSIS, a multi-criteria decision-making method, with AHP and Shannon Entropy improves the decision-making processes in spatial analysis. Kumar [14] performed risk assessment using a fuzzy-based analytical hierarchy process. Gundogdu et al. [8] stated that by integrating the Illustrated Fuzzy AHP and Linear Assignment Model, more precise and reliable results are obtained in decision processes involving uncertainty. Duleba et al. [5] used the interval-valued global fuzzy AHP method to provide a more effective evaluation of uncertain data. Navdeep and Dixit [1] performed spatial risk assessment by integrating AHP and fuzzy AHP models with the Shannon Entropy and frequency ratio method. Nasrullah et al. [16] proposed the use of RIPC4 and the AHP in the risk assessment of e-government to analyze risk priorities. Kaur et al. [12] identified and prioritized risks in decentralized finance using the fuzzy analytical hierarchy process (FAHP). Hybrid model studies using Extended Fuzzy Entropy and 2D FAHP together are almost non-existent in the literature. Keleş [13] evaluates the trade facilitation performance of E7 countries by integrating multiple weighting and ranking methods.

When reviewing the literature, there is no theoretical proposition regarding the weighting of a large number of main criteria that are considered to be of equal importance and have different and large numbers of sub-criteria. This leads to misleading results in determining the riskiness levels of the criteria and revealing the cost levels of this riskiness. In the process steps used in decision-making methods, even if there are different numbers of sub-criteria, the aforementioned problems persist since they are weighted with equal importance. Therefore, in order to solve this problem, the Yaşar-Terzioğlu approach is proposed in this paper, which takes into account the number of sub-criteria when applying weighting methods. In this approach, in order to increase the degree of representativeness of uncertainties in conflicting criteria evaluations, a correction term $\sqrt{\frac{T-t_i}{T-1}}$ that takes into account the differences in the number of sub-criteria is integrated into the fuzzy entropy method, so that the risk cost levels of the main criteria of equal importance differ according to the number of sub-criteria. Therefore, the application of existing hybrid models differs from the studies in literature with the addition of the correction factor proposed in the paper. In addition, interval values are needed to create the risk pool for the riskiness levels. At the end of the solution phase of the fuzzy AHP method, ranking the criteria based on the crisp value does not make it possible to form the risk pool. For this reason, in this article, it is shown that the fuzzy AHP method can be combined with the α-alpha cut-off method to ensure the formation of the risk pool, and that the solution can be obtained based on the two-dimensional confidence interval instead of the crisp value until the last stage of the solution. Thus, unlike the hybrid models in literature, the criteria rankings are analyzed as intervals instead of crisp values. As a result, the proposed approach differs from other hybrid models in literature, firstly, by applying the criteria weight calculation steps presented in the paper and secondly, by maintaining the fuzzy structure until the end of the process and considering the process steps for creating a risk pool.

Hybrid model studies using Extended Fuzzy Entropy and 2D Fuzzy Analytic Hierarchy Process (AHP) together are almost non-existent in the literature. However, by including a risk response stage and a classification such as risk acceptance/mitigation/deferral, an approach that does not only focus on measuring and ranking risk is also presented in the literature. In this article, the Extended F-Entropy Method with Correction Factor- Based 2D-FAHP Method is presented, and an application example is given.

2. Methodology

While evaluations can be made intuitively when a single criterion is considered in the decision-making processes, evaluations become complex when more than one criterion is involved. If the main criteria in the decision matrices based on expert opinions are considered equally important even though they have sub-criteria of different dimensions, no definite judgment can be made in their importance ranking. Therefore, the AHP method is not an appropriate method in cases where there is uncertainty due to the size of the comparisons and the complexity of the calculations. Since the same decision matrix is used in the fuzzy AHP method, which is a transformation of the AHP method in modeling uncertainty, it cannot provide a successful solution in providing a clear ranking even if the fuzzy structure is switched. In addition, since the clarification process step used to reach the solution in the fuzzy AHP method converts the decision matrix into a definite judgment matrix and reduces it to a crisp value, the fuzzy structure disappears, and the relative risk matrix cannot be created.

To achieve a crisp importance ranking for overlapping criteria, this paper proposes preserving the fuzzy structure by presenting the results as a range, rather than reducing them to integer values. The alpha cut method reconstructs the fuzzy decision matrix within the confidence interval boundaries. In the following stage, each criterion's two-dimensional fuzzy entropy (F-entropy) weights must be calculated using the number of sub-criteria as a multiplier. Finally, by multiplying the weight obtained from the two-dimensional F-entropy method with the two-dimensional decision matrix generated using the alpha value, a two-dimensional fuzzy AHP (2D-FAHP) solution can be obtained to obtain the criteria's crisp ranking

When dealing with complex decision elements, the AHP method, which is based on the assumption of clustering decision elements based on common characteristics, creates a hierarchical structure with the goal at the top level. At the next level, criteria and, if any, subcriteria affecting the goal are identified, and a structure of alternatives determining the outcome is developed. The pairwise comparison matrix, based on the judgments of the decision maker, is constructed using fuzzy triangular numbers, where d_{ij}^k represents the k-th decision maker's preference of the i-th criterion over the j-th criterion. The triangular number dimension is defined as $a_{ij}^k = (a_1, a_2, a_3)$, resulting in the fuzzy decision matrix $\tilde{A}^k = (\tilde{a}_{nn}^k)$. The confidence interval of the triangular values obtained by comparing the fuzzy comparison values of each criterion is defined at the α-alpha level as $l_{ij} = (\tilde{a}_2 - \tilde{a}_1)\alpha + \tilde{a}_1$ and $u_{ij} = \tilde{a}_3 - (\tilde{a}_3 - \tilde{a}_2)\alpha$ for $0 \leq \alpha < 1$. The triangular fuzzy number is characterized as $A_\alpha = [\tilde{a}_1^\alpha, \tilde{a}_3^\alpha] = [l_{ij}, u_{ij}]$, thus reaching the two-dimensional fuzzy confidence interval values for each criterion [11]. For $\alpha = 1$, the values of l_{ij} and u_{ij} are the same as the triangular fuzzy values. Moreover, because no confidence interval is formed, the range for the α-cut value is proposed as $0 \leq \alpha < 1$.

In MCDM problems with uncertain judgments, fuzzy and interval numbers are used to weight criteria with F-entropy based on the α-cut method [10]. The decision matrix for the problem is constructed in the following manner:

$$D = \begin{matrix} \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{i1} & x_{i2} & \cdots & x_{in} \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix} \\ \tilde{w}_1 \;\; \tilde{w}_2 \;\; \cdots \;\; \tilde{w}_n \end{matrix} \tag{1}$$

where x_{ij} represents the value of the i-th alternative $(i = 1, 2, \ldots, m)$ with respect to the j-th evaluation criterion $(j = 1, 2, \ldots, n)$, and $\tilde{w}_j$, which represents the weight of the j-th criterion [15]. When $(\tilde{x}_{ij})_\alpha = \{x \in \mathbb{R} \mid \mu_{\tilde{x}_{ij}}(x) \geq \alpha\}$, the α-cut set is represented in the form of an interval number as:

$$[\tilde{x}_{ij}^L(\alpha), \tilde{x}_{ij}^U(\alpha)] = \big[\min\left\{x_{ij} \mid x_{ij} \in \mathbb{R} \text{ and } \mu_{\tilde{x}_{ij}}(x_{ij}) \geq \alpha\right\},$$

$$\max\left\{x_{ij} \mid x_{ij} \in \mathbb{R} \text{ and } \mu_{\tilde{x}_{ij}}(x_{ij}) \geq \alpha\right\}\big],$$

where $0 < \alpha \leq 1$. In the first step of the Entropy method,the following formula are used to create a normalized decision matrix to normalize criteria with different units to the range $[0, 1]$:

$$p_{ij}^l = \frac{x_{ij}^l}{\sum_{i=1}^n x_{ij}^u}, \quad p_{ij}^u = \frac{x_{ij}^u}{\sum_{i=1}^n x_{ij}^u} \tag{2}$$

The entropy (uncertainty measure) values for the evaluation criterion are calculated as:

$$e_j^l = \min\left\{-k\sum_{i=1}^m p_{ij}^l \ln p_{ij}^l,\; k\sum_{i=1}^n p_{ij}^u \ln p_{ij}^u\right\}$$

$$e_j^u = \max\left\{-k\sum_{i=1}^{m} p_{ij}^l \ln p_{ij}^l,\ k\sum_{i=1}^{n} p_{ij}^u \ln p_{ij}^u\right\} \tag{3}$$

where $k = (\ln(m))^{-1}$ and $0 \leq e_j \leq 1$.In the next step, after calculating the degrees of differentiation of the information expressed as $d_i^l = 1 - e_{ij}^u$ and $d_i^u = 1 - e_{ij}^l$, the weight values for the criteria are obtained by satisfying the condition $\sum_{j=1}^{n} w_j = 1$, as follows [15];

$$w_i^l = \frac{d_j^l}{\sum_{j=1}^{n} d_j^u} \qquad w_i^u = \frac{d_j^u}{\sum_{j=1}^{n} d_j^l} \tag{4}$$

This paper proposes employing the two-dimensional decision matrix from the FAHP method using the α-cut method instead of the decision matrix defined in Equation (1) of the F-entropy method. In this context, for the value of the j-th criterion (for $j = 1, 2, \ldots, n$) with respect to the i-th criterion (for $i = 1, 2, \ldots, n$), the element $x_{ij} = (l_{ij}, u_{ij})$ represents a two-dimensional fuzzy number. Thus, the two-dimensional fuzzy decision matrix is constructed in the following manner:

$$\tilde{A} = [x_{ij}]_{n\times n} = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{n1} & x_{n2} & \cdots & x_{nn} \end{bmatrix} \tag{5}$$

where $x_{ij} = (l_{ij}, u_{ij})$ denotes the two-dimensional fuzzy relative importance value of the j-th criterion with respect to the i-th criterion, and l_{ij} and u_{ij} are expressed as the lower and upper bounds, respectively, of the relative importance value x_{ij}^{α}. To calculate the values in the normalized decision matrix for each criterion, we first obtained the vector sum of each x_i. When calculating the power of (-1) of the total vector, the lower (l_{ij}) and upper (u_{ij}) values are swapped, transforming the triangular number-based decision matrix into a two-dimensional fuzzy number form.

In addition to the normalization process in Equation (2), which employs Shannon's [19] extended F-entropy method, this study recommends incorporating subcriteria ratios when the relevant main criteria of equal importance have different numbers of subcriteria. Shannon Entropy is an approach that forms the basis of other entropy methods and is preferred as the most convenient method because it minimizes the computational burden. In this context, In this context, this paper proposed the Yaşar-Terzioğlu approach that uses the weight multiplier $\sqrt{\frac{T-t_i}{T-1}}$ for the sub-criteria if the ratio of the number of the i-th criterion subcriteria, t_i, to the total number of sub-criteria, T, is greater than 5%. The normalization process for calculating the fuzzy weight value for the i-th criterion, which includes the added weight multiplier for correction, should be carried out in two dimensions using the following formulations:

$$p_{ij}^l = \frac{x_{ij}^l}{\sum_{i=1}^{n} x_{ij}^u} \times \sqrt{\frac{T-t_i}{T-1}}, \quad p_{ij}^u = \frac{x_{ij}^u}{\sum_{i=1}^{n} x_{ij}^l} \times \sqrt{\frac{T-t_i}{T-1}} \tag{6}$$

where the calculations are performed in two dimensions. Equation (3) defines the lower and upper bounds for the F-entropy (uncertainty measure) values related to the evaluation criterion for $j = 1, 2, \ldots, n$:

$$e_j^l = -k\sum_{i=1}^{m} p_{ij}^l \ln p_{ij}^l, \quad e_j^u = -k\sum_{i=1}^{m} p_{ij}^u \ln p_{ij}^u \tag{7}$$

where the two-dimensional lower and upper bounds are calculated. The F-Entropy weights for the criteria are proposed to be obtained using the formulation:

$$w_j^l = \frac{1 - e_j^u}{\sum_{j=1}^n d_j^l + \sum_{j=1}^n d_j^u}, \quad w_j^u = \frac{1 - e_j^l}{\sum_{j=1}^n d_j^l + \sum_{j=1}^n d_j^u} \tag{8}$$

instead of the formula given in Equation (4), where $\sum_{j=1}^n d_j^l = \sum_{j=1}^n (1 - e_j^l)$ and $\sum_{j=1}^n d_j^u = \sum_{j=1}^n (1 - e_j^u)$.

The paper's proposed 2D-FAHP method uses the α-cut method to reduce the two-dimensional fuzzy decision matrix to two dimensions. It incorporates the two-dimensional F-Entropy weights w_j^l and w_j^u as row multipliers for the main criteria, as suggested in the paper.

The FAHP comparison values weighted according to the two-dimensional F-Entropy method should be calculated as two-dimensional values for each criterion, where $\tilde{X} = [x_{ij} \cdot w_j^{(l,u)}]_{(n \times n)} = [\tilde{x}_{ij}]_{(n \times n)}$, with $\tilde{x}_{ij} = (x_{ij}^l \cdot w_j^l, x_{ij}^u \cdot w_j^u) = (\tilde{x}_{ij}^l, \tilde{x}_{ij}^u)$. In the 2D-FAHP framework, the normalization process should be performed using the following formulation, incorporating the relevant criterion's F-entropy weight multiplier into the row operations:

$$\tilde{a}_{ij}^l = \frac{\tilde{x}_{ij}^l}{\sum_{i=1}^n \tilde{x}_{ij}^u} \quad \text{and} \quad \tilde{a}_{ij}^u = \frac{\tilde{x}_{ij}^u}{\sum_{i=1}^n \tilde{x}_{ij}^l} \tag{9}$$

The geometric mean of the two-dimensional criteria weights' lower and upper bound values should be used for the 2D-FAHP method proposed in this paper, rather than the arithmetic mean suggested by Buckley [3]. To obtain the two-dimensional criterion weights, we use the following formula:

$$w_i^{(l,u)} = \begin{cases} w_i^l = \left(\prod_{j=1}^n \tilde{a}_{ij}^l\right)^{\frac{1}{n}} \\ w_i^u = \left(\prod_{j=1}^n \tilde{a}_{ij}^u\right)^{\frac{1}{n}} \end{cases} \tag{10}$$

In the paper context, Hurwicz's realism criterion is included as a smoothing process to allow the decision-maker to incorporate their emotions into the process [9]. Using the fuzzy two-dimensional weights obtained from Equation (10), the fuzzy membership function is defined with the risk index β as:

$$G_i = \left((w_i^{(l,u)})^\alpha\right)^\beta = \beta \cdot w_i^l + (1 - \beta) \cdot w_i^u, \quad 0 \leq \beta \leq 1,\ 0 \leq \alpha \leq 1,\ i < j \tag{11}$$

The risk index β is a measure of the degree of risk in an environment: the values of 0, 0.5, and 1 indicate a high-risk (pessimistic), moderate-risk (moderate), and low-risk (optimistic) environments, respectively [17].

Probability	**30–45**	**16–29**	**0–15**
High	Pool 1	Pool 2	Pool 2
Medium	Pool 2	Pool 2	Pool 3
Low	Pool 3	Pool 3	Pool 4
Pools	**Risk Mitigation Approach**	**Pools**	**Risk Mitigation Approach**
Pool 1	Reduce the Risk	Pool 3	Delay or accept risk
Pool 2	Reduce or delay risk	Pool 4	Accept the risk

Table 1: Relative Risk Matrix

Moreover, an approach is suggested in this paper to streamline the risk assessment process by incorporating Hurwicz's realism criterion into the OCTAVE Allegro method and converting it into a risk matrix (Table 1). Scores are computed for each environmental condition to quantify the criteria. Risk score ranges are established, and risk pools are generated by ranking the criteria with the highest scores based on the riskiest environment. Risks earning the highest scores are Pool 1; the next highest score range, Pool 2; risks within the next highest score range are assigned to Pool 3; and risks within the lowest score range are assigned to Pool 4. Distinct risk pools are established for criteria and alternatives, with each pool allocated to evenly distributed segments based on their relative risk score and probability of occurrence [4].

3. Application

The main and sub-criteria for selecting risky assets in the scope of this paper are based on the Digital Transformation Office's expert opinions, accessible open-source guides, and related literature reviews. This article considers the AHP method by Saaty [18] as the structure used in the selection decisions of the riskiest criteria addressing the security risk of digital information assets. For the AHP method, the hierarchical structure of the Security Risks for Digital Information Assets, which includes the main criteria and sub-criteria, is grouped (Table 2). The hierarchical structure obtained in Table 2 is based on the Trakya University Scientific Research Project No. 2021/133 "E-Government Information Security Risk Assessment: Artificial Neural Network Modeling." Pairwise comparison matrices were created with the data used in the hierarchical structure grouping.

Networks & Systems	**Application & Data Security**	**Portable Device & Environment Security**
Hardware Inventory	File/Resource Security	Smartphone/Tablet
Software Inventory	External Integrations	Laptop Security
Threat/Vulnerability Mgmt.	Installation/Config.	Media Security
Email Security	Secure Dev.	Comm. Security
Malware Protection	Logging Mgmt.	
Network Security	Authentication	
DLP	Malicious Prevention	
Monitoring	Session Auth. Mgmt.	
Virtualization	DB Management	
Incident Mgmt.	Authorization	
Pen. Tests		
Access Mgmt.		
BC/DR Mgmt.		
Remote Work		

IoT & Device Security	**Physical Security**	**Personnel Security**
Network Services	General Precautions	General Precautions
Internal Storage	System Room Security	Awareness Activities
Auth./Access	TEMPEST Protection	Supplier Relations
API Security		
Other Measures		

Table 2: E-Government Information Security Risk Structure

At the stage of constructing the pairwise comparison matrices, complementings the subjective judgments of the experts, the pairwise comparison matrix of the main criteria and the normalized comparison matrix are obtained in Table 3. In the pairwise comparison matrix, where the relative importance of the criteria against each other is determined, the values in each column are normalized by dividing by the sum of the relevant columns, and then the weight vector of the criteria is obtained by averaging each row. When the importance weights of the criteria are analyzed, the Application & Data Security and Portable Device & Environment criteria have the same importance ranking.

Pairwise Comparison Matrix						
	N&S	A & DS	PD & E	IoT	SPP	SP
Networks & Systems	1,00	0,33	0,33	4,00	2,00	4,00
Application & Data Security	3,00	1,00	1,00	6,00	5,00	4,00
Portable Device & Environment	3,00	1,00	1,00	6,00	5,00	4,00
Internet of Things	0,25	0,17	0,17	1,00	0,50	0,33
Security of Physical Places	0,50	0,20	0,20	2,00	1,00	3,00
Security of Personnel	0,25	0,25	0,25	3,00	0,33	1,00
Normalized Pairwise Comparison Matrix						
	N&S	A & DS	PD & E	IoT	SPP	SP
Networks & Systems	0,13	0,11	0,11	0,18	0,14	0,24
Application & Data Security	0,38	0,34	0,34	0,27	0,36	0,24
Portable Device & Environment	0,38	0,34	0,34	0,27	0,36	0,24
Internet of Things	0,03	0,06	0,06	0,05	0,04	0,02
Security of Physical Places	0,06	0,07	0,07	0,09	0,07	0,18
Security of Personnel	0,03	0,08	0,08	0,14	0,02	0,06
Weight Vector						
Networks & Systems: 0,153			Internet of Things: 0,041			
Application & Data Security: 0,322			Security of Physical Places: 0,090			
Portable Device & Environment: 0,322			Security of Personnel: 0,070			
Consistency Evaluation of the Corresponding Matrix						
$\lambda_{\max} = 6{,}4$	Consistency Index = 0,07		Consistency Ratio = 0,0585			

Table 3: AHP Pairwise Comparison Matrix and Consistency Evaluation of Main Criteria

Since the pairwise comparison matrix is consistent and the consistency ratio is less than 0.10 in Table 3, the FAHP method based on the Buckley approach is used to eliminate the judgment uncertainty in the criteria with equal importance ranking. FAHP better manages uncertain and imprecise data. The evaluations of decision makers are expressed using fuzzy numbers instead of integers, and thus the uncertainty of subjective judgments is modeled. In Table 4, the AHP decision matrix is reconstructed according to the triangular fuzzy numbers and a fuzzy pairwise comparison matrix is obtained. After the relevant normalization process steps, the fuzzy triangular weights of the criteria are obtained, and the Application & Data Security and Portable Device & Environment criteria have the same importance ranking.

Fuzzy Pairwise Comparison Matrix						
	N&S	A & DS	PD & E	IoT	SPP	SP
Networks & Systems	(1,1,1)	(1/4,1/3,1/2)	(1/4,1/3,1/2)	(3,4,5)	(1,2,3)	(3,4,5)
Application & Data Security		(1,1,1)	(1,1,1)	(5,6,7)	(4,5,6)	(3,4,5)
Portable Device & Environment			(1,1,1)	(5,6,7)	(4,5,6)	(3,4,5)
Internet of Things				(1,1,1)	(1/3,1/2,1)	(1/4,1/3,1/2)
Security of Physical Places					(1,1,1)	(1,1,1)
Security of Personnel						(1,1,1)
Fuzzy Triangular Weights						
Networks & Systems	0,00033475		0,00493767		0,07811667	
Application & Data Security	0,07141402		0,49993887		3,49962672	
Portable Device & Environment	0,07141402		0,49993887		3,49962672	
Internet of Things	0,00000020		0,00000161		0,00002777	
Security of Physical Places	0,00000551		0,00005555		0,00078117	
Security of Personnel	0,00000952		0,00006510		0,00061722	
Defined Values and Importance Ranking						
Networks & Systems	0,027796	3	Internet of Things	0,000010	6	
Application & Data Security	1,356993	1*	Security of Physical Places	0,000281	4	
Portable Device & Environment	1,356993	1*	Security of Personnel	0,00231	5	

Table 4: Fuzzy Pairwise Comparison Matrix and Evaluation Results

When the AHP results (Table 3) and FAHP results (Table 4) are analyzed, the importance rankings of the Application & Data Security and Portable Device & Environment criteria still overlap. To determine the continuity of the overlap in the importance ranking at different levels of uncertainty, the alpha-cutting method is examined using the fuzzy pairwise comparison matrix in Table 4. In Table 5, the Hurwicz coefficient and alpha-intercept values are used together to obtain the confidence levels of the evaluations of the decision makers and the net importance rankings by including the uncertain environmental conditions in the method.

Main Criteria						
Hurwicz Coefficient	$\beta = 0$					
Alpha-Cut Values	**0**	**0,2**	**0,4**	**0,6**	**0,8**	**1,0**
Networks & Systems	0,19	0,18	0,18	0,17	0,16	0,15
Application & Data Security	0,32	0,32	0,32	0,32	0,32	0,32
Portable Device & Environment	0,32	0,32	0,32	0,32	0,32	0,32
Internet of Things	0,04	0,04	0,04	0,04	0,04	0,04
Security of Physical Places	0,05	0,05	0,06	0,06	0,06	0,07
Security of Personnel	0,06	0,06	0,06	0,07	0,07	0,07
Hurwicz Coefficient	$\beta = 0{,}5$					
Alpha-Cut Values	**0**	**0,2**	**0,4**	**0,6**	**0,8**	**1,0**
Networks & Systems	0,16	0,16	0,16	0,16	0,16	0,15
Application & Data Security	0,32	0,32	0,32	0,32	0,32	0,32
Portable Device & Environment	0,32	0,32	0,32	0,32	0,32	0,32
Internet of Things	0,04	0,04	0,04	0,04	0,04	0,04
Security of Physical Places	0,06	0,06	0,06	0,07	0,07	0,07
Security of Personnel	0,07	0,07	0,07	0,07	0,07	0,07
Hurwicz Coefficient	$\beta = 1$					
Alpha-Cut Values	**0**	**0,2**	**0,4**	**0,6**	**0,8**	**1,0**
Networks & Systems	0,13	0,14	0,14	0,15	0,16	0,16
Application & Data Security	0,31	0,31	0,31	0,31	**0,31***	0,32
Portable Device & Environment	0,31	0,31	0,31	0,31	**0,32***	0,32
Internet of Things	0,04	0,04	0,04	0,04	0,04	0,04
Security of Physical Places	0,09	0,08	0,08	0,07	0,07	0,07
Security of Personnel	0,10	0,09	0,09	0,08	0,08	0,07

Table 5: General Weights for Hurwicz Coefficient (β) and Alpha-Cut Values (α)

As shown in Table 5, the Application & Data Security and Portable Device & Environment criteria have the same importance ranking even if all uncertain risky situations are included in the process. Only in the 0.8 alpha-intercept uncertainty environment under β=1, which refers to the risk-free (optimistic) environment conditions, the importance ranking changes. For the other conditions, the overlap in the importance ranking continues. As a result, when Tables 3–5 are considered, it is determined that the overlap in the importance rankings of the Application & Data Security and Portable Device & Environment criteria continues and the approaches in the literature cannot eliminate this overlap, especially in risky and medium-risk environments.

This paper criticizes using a fuzzy structure to obtain the importance ranking and then clarifying this structure and reducing it to crisp values. Instead, it is more effective to perform the importance ranking directly within the fuzzy structure and compare interval values instead of crisp values. Accordingly, the Hurwicz coefficients given in Table 5 should not be used to return to the crisp value and instead be evaluated directly by the alpha-intercept method. Thus, when obtaining the importance ranking in the fuzzy model approaches, the uncertainty will be reflected as a range instead of a point. Typically, solving a system that starts with a fuzzy structure by reducing it to a single value will not give realistic results. For this reason, the following steps should be applied in order.

In Table 6, the AHP decision matrix is first transformed into a fuzzy triangular decision matrix to address fuzziness. Within the scope of the method proposed, the α-alpha cut-off method is used to calculate the lower and upper bound values of the fuzzy triangular values for the 0.8 environment level, which indicates that the uncertainty is high (other alpha cut-off values can also be examined if desired by the researchers) and the pairwise comparison matrix is obtained in two dimensions.

			AHP Decision Matrix			
	Net. & Sys	App. & Sec	Port. Dev	IoT	Phys. Sec	Pers. Sec
Net. & Sys	1,00	0,33	0,33	4,00	2,00	4,00
App. & Sec	3,00	1,00	1,00	6,00	5,00	4,00
Port. Dev	3,00	1,00	1,00	6,00	5,00	4,00
IoT	0,25	0,17	0,17	1,00	0,50	0,33
Phys. Sec	0,50	0,20	0,20	2,00	1,00	3,00
Pers. Sec	0,25	0,25	0,25	3,00	0,33	1,00
			Fuzzy Triangular Decision Matrix			
	Net. & Sys	App. & Sec	Port. Dev	IoT	Phys. Sec	Pers. Sec
Net. & Sys	(1,1,1)	(0.25,0.33,0.5)	(0.25,0.33,0.5)	(3,4,5)	(1,2,3)	(3,4,5)
App. & Sec	(2,3,4)	(1,1,1)	(1,1,1)	(5,6,7)	(4,5,6)	(3,4,5)
Port. Dev	(2,3,4)	(1,1,1)	(1,1,1)	(5,6,7)	(4,5,6)	(3,4,5)
IoT	(0.20,0.25,0.33)	(0.14,0.17,0.20)	(0.14,0.17,0.20)	(1,1,1)	(0.33,0.5,1)	(0.25,0.33,0.5)
Phys. Sec	(0.33,0.50,1)	(0.17,0.20,0.25)	(0.17,0.20,0.25)	(1,2,3)	(1,1,1)	(1,1,1)
Pers. Sec	(0.20,0.25,0.33)	(0.20,0.25,0.33)	(0.20,0.25,0.33)	(2,3,4)	(1,1,1)	(1,1,1)
			Two-Dimensional Reduced Decision Matrix with Alpha-Cut Method			
α=0.8	Net. & Sys	App. & Sec	Port. Dev	IoT	Phys. Sec	Pers. Sec
Net. & Sys	(1,1)	**(0.32, 0.37)**	(0.32,0.37)	(3.80, 4.20)	(1.80, 2.20)	(3.80, 4.20)
App. & Sec	(2.80, 3.20)	(1,1)	(1,1)	(5.80, 6.20)	(4.80, 5.20)	(3.80, 4.20)
Port. Dev	(2.80, 3.20)	(1,1)	(1,1)	(5.80, 6.20)	(4.80, 5.20)	(3.80, 4.20)
IoT	(0.24,0.27)	(0.16, 0.17)	(0.16,0.17)	(1,1)	(0.47,0.60)	(0.32, 0.37)
Phys. Sec	(0.47, 0.60)	(0.19,0.21)	(0.19, 0.21)	(1.80, 2.20)	(1,1)	(1,1)
Pers. Sec	(0.24, 0.27)	(0.24, 0.27)	(0.24, 0.27)	(2.80, 3.20)	(1,1)	(1,1)
Total	7.55; 8.53	2.91; 3.02	2.91; 3.02	21.00; 23.00	13.87; 15.20	13.72; 14.97

*Comparison of **Network & System** with **Application & Data Security** (0.25;0.33;0.50) for* $\alpha = 0.8$*: Two-Dimensional Values for Comparison of Network & System with Application & Data Security:*

$Networks\&Systems_{l_{12}} = [0.8 \times (0.33 - 0.25)] + 0.25 = 0.314 \approx 0.32$

$Networks\&Systems_{u_{12}} = 0.50 - [(0.50 - 0.33) \times 0.8] = 0.364 \approx 0.37$

Table 6: Calculation of the Two-Dimensional Decision Matrix with the α-Cut Method

The normalization of the 2D decision matrix obtained by the alpha-cutting method in Table 6 is performed by integrating the correction term $\sqrt{\frac{T-t_i}{T-1}}$ proposed in Equation (6) into the fuzzy entropy method in Table 7. Additionally, as proposed in Equations (7) and (8), the 2D F-entropy values ($e_j^{(l,u)}$) and weights ($w_j^{(l,u)}$) for the main criteria are also obtained in Table 7. The 2D F-entropy importance weights, obtained as suggested in Table 6, should be used as the relative importance multiplier of the criteria in the 2-dimensional FAHP method. Thus, the importance values of the overlapping criteria are differentiated.

Normalized Decision Matrix Using the Extended F-Entropy Method with a Correction Factor						
$\alpha = 0.8$	Net. & Sys	App. & Sec	Port. Dev	IoT	Phys. Sec.	Pers. Sec.
Net. & Sys.	(0.09,0.10)	**(0.09, 0.11)**	(0.10,0.12)	(0.15, 0.18)	(0.11, 0.15)	(0.24, 0.29)
App. & Sec.	(2.80, 3.20)	(1,1)	(1,1)	(5.80, 6.20)	(4.80, 5.20)	(3.80, 4.20)
Port. Dev	(2.80, 3.20)	(1,1)	(1,1)	(5.80, 6.20)	(4.80, 5.20)	(3.80, 4.20)
IoT	(0.24,0.27)	(0.16, 0.17)	(0.16,0.17)	(1,1)	(0.47,0.60)	(0.32, 0.37)
Phys. Sec	(0.47, 0.60)	(0.19,0.21)	(0.19, 0.21)	(1.80, 2.20)	(1,1)	(1,1)
Pers. Sec	(0.24, 0.27)	(0.24, 0.27)	(0.24, 0.27)	(2.80, 3.20)	(1,1)	(1,1)
Sub-Criteria Ratios	14/39	10/39	4/39	5/39	3/39	3/39
Correction Factor Weight Multiplier	0.81	0.87	0.96	0.95	0.97	0.97

Comparison of ***Network & System*** *with* ***Application & Data Security*** *Normalized Weights*

$$p_{ij}^{l} = \frac{x_{ij}^{l}}{\sum_{i=1}^{n} x_{ij}^{u}} \times \sqrt{\frac{T-t_i}{T-1}}, \quad p_{ij}^{u} = \frac{x_{ij}^{u}}{\sum_{i=1}^{n} x_{ij}^{l}} \times \sqrt{\frac{T-t_i}{T-1}}$$

$$\text{Networks\&Systems}_{l_{12}}^{l} = \left(\frac{0{,}32}{3{,}02}\right) \times \sqrt{\frac{39-10}{39-1}} = 0{,}092$$

$$\text{Networks\&Systems}_{l_{12}}^{u} = \left(\frac{0{,}37}{2{,}91}\right) \times \sqrt{\frac{39-10}{39-1}} = 0{,}110$$

Two-Dimensional Fuzzy Entropy Method Decision Matrix Using the Number of Sub-Criteria						
$\alpha = 0.8$	Net. & Sys	App. & Sec	Port. Dev	IoT	Phys. Sec.	Pers. Sec.
Net. & Sys.	(-0.22, -0.24)	**(-0.21, -0.24)**	(-0.23, -0.25)	(-0.29, -0.31)	(-0.24, -0.28)	(-0.34, -0.36)
App. & Sec.	(-0.35, -0.36)	(-0.35, -0.36)	(-0.36, -0.36)	(-0.34, -0.35)	(-0.36, -0.36)	(-0.34, -0.36)
Port. Dev.	(-0.35, -0.36)	(-0.35, -0.36)	(-0.36, -0.36)	(-0.34, -0.35)	(-0.36, -0.36)	(-0.34, -0.36)
IoT	(-0.08, -0.10)	(-0.14, -0.15)	(-0.15, -0.16)	(-0.13, -0.14)	(-0.10, -0.13)	(-0.08, -0.09)
Phys. Sec.	(-0.13, -0.17)	(-0.16, -0.17)	(-0.17, -0.18)	(-0.19, -0.22)	(-0.17, -0.18)	(-0.17, -0.18)
Pers. Sec.	(-0.08, -0.10)	(-0.18, -0.20)	(-0.19, -0.21)	(-0.24, -0.27)	(-0.17, -0.18)	(-0.17, -0.18)

Comparison of ***Network & System*** *with* ***Application & Data Security*** *Two dimensional Fuzzy Entropy values*

$$e_{j}^{l} = -k \sum_{j=1}^{m} p_{ij}^{l} \ln p_{ij}^{l}, \quad e_{j}^{u} = -k \sum_{i=1}^{m} p_{ij}^{u} \ln p_{ij}^{u}$$

$$\text{Networks\&Systems}_{l_{12}} = 0{,}092 \times \ln(0{,}092) = -0{,}219$$

$$\text{Networks\&Systems}_{u_{12}} = 0{,}110 \times \ln(0{,}110) = -0{,}243$$

$$\text{Networks\&Systems } e_{12}^{l} = [(-0{,}219) + (-0{,}359) + (-0{,}359) + (-0{,}143) + (-0{,}161) + (-0{,}185)] \times (-0{,}5581) = 0{,}80$$

$$\text{Networks\&Systems } e_{12}^{u} = [(-0{,}243) + (-0{,}361) + (-0{,}361) + (-0{,}154) + (-0{,}174) + (-0{,}202)] \times (-0{,}5581) = 0{,}83$$

Calculation of Two-Dimensional Fuzzy Entropy Criterion Weights						
1/ln=0.5581	**Networks & Systems**	**Application & Data Security**	**Portable Device & Environment**	**Internet of Things**	**Security of Physical Places**	**Security of Personnel**
$e_{j}^{(l,u)}$	(0.69,0.76)	**(0.80, 0.83)**	(0.83, 0.86)	(0.86, 0.94)	(0.80, 0.85)	(0.82, 0.87)
$d_{j}^{(l,u)}$ = 1- $e_{j}^{(l,u)}$	(0.31, 0.24)	**(0.20, 0.17)**	(0.17, 0.14)	(0.14, 0.06)	(0.20, 0.15)	(0.18, 0.13)
$\sum_{j=1}^{n} d_{j}^{l} + \sum_{j=1}^{n} d_{j}^{u}$	2,08					
Two-Dimensional Fuzzy Entropy Weights	(0.117,0.148)	**(0.079, 0.097)**	(0.065, 0.083)	(0.031, 0.065)	(0.070, 0.096)	(0.064, 0.085)

Comparison of ***Network & System*** *with* ***Application & Data Security*** *Two dimensional Fuzzy Entropy weights*

$$\left(w_{j}^{l} = \frac{1-e_{j}^{u}}{\sum_{j=1}^{n} d_{j}^{l} + \sum_{j=1}^{n} d_{j}^{u}}, \quad w_{j}^{u} = \frac{1-e_{j}^{l}}{\sum_{j=1}^{n} d_{j}^{l} + \sum_{j=1}^{n} d_{j}^{u}} \right)$$

$$\text{Networks \& Systems: } w_{1}^{l} = \frac{0.17}{2.08} \approx 0.079, \quad w_{1}^{u} = \frac{0.20}{2.08} \approx 0.097$$

$$\Rightarrow w_{1}^{(l,u)} = (0.079,\ 0.097)$$

(Two-Dimensional Entropy Weights for the comparison of the first criterion 'Networks & Systems' with the second criterion 'Application & Data Security')

Table 7: Calculation of Two-Dimensional Fuzzy Entropy Weights

In Table 8, the relative importance ($w_j^{(l,u)}$) weights obtained by the F-entropy method, in which the correction term proposed in the article is integrated, create a difference in the importance rankings of the overlapping criteria in the 2D fuzzy AHP method. The weights w_i^l and w_i^u of the fuzzy 2-dimensional entropy are applied to the fuzzy decision matrix, reduced to two dimensions by the alpha-cutting method, as row multipliers of the relevant main criteria, as proposed. By adding the fuzzy entropy relative importance multiplier of the relevant criterion to the row operations, the normalization process is applied using Equation (9) within the scope of the 2D FAHP. In the calculation of the weights of the criteria, the geometric mean is used to reduce the effect of extreme values between the lower and upper limits. Using geometric means, a 2-dimensional prioritization (weight) vector is obtained, and the importance rankings are made according to the lower and upper bound ranges. In this way, there is no need for any reduction to the net value as a result of any calibration process.

Two-Dimensional FAHP Decision Matrix						
$\alpha = 0.8$	Net. & Sys.	App. & Sec.	Port. Dev.	IoT	Phys. Sec.	Pers. Sec.
Net. & Sys.	(1,1)	**(0.32, 0.37)**	(0.32, 0.37)	(3.80, 4.20)	(1.80, 2.20)	(3.80, 4.20)
App. & Sec.	(2.80, 3.20)	(1, 1)	(1, 1)	(5.80, 6.20)	(4.80, 5.20)	(3.80, 4.20)
Port. Dev.	(2.80, 3.20)	(1, 1)	(1, 1)	(5.80, 6.20)	(4.80, 5.20)	(3.80, 4.20)
IoT	(0.24, 0.27)	(0.16, 0.17)	(0.16, 0.17)	(1, 1)	(0.47, 0.60)	(0.32, 0.37)
Phys. Sec.	(0.47, 0.60)	(0.19, 0.21)	(0.19, 0.21)	(1.80, 2.20)	(1, 1)	(1, 1)
Pers. Sec.	(0.24, 0.27)	(0.24, 0.27)	(0.24, 0.27)	(2.80, 3.20)	(1, 1)	(1, 1)
Total	(7.55, 8.53)	**(2.91, 3.02)**	(2.91, 3.02)	(21.0, 23.0)	(13.87, 15.20)	(13.72, 14.97)
Calculation of 2D Fuzzy AHP Criterion Weights						
$\alpha = 0.8$	Net. & Sys.	App. & Sec.	Port. Dev.	IoT	Phys. Sec.	Pers. Sec.
2D Fuzzy Entropy Weights	**(0.117, 0.148)**	(0.079, 0.097)	(0.065, 0.083)	(0.031, 0.065)	(0.070, 0.096)	(0.064, 0.085)
Net. & Sys.	(0.01, 0.02)	**(0.012, 0.019)**	(0.012, 0.019)	(0.019, 0.030)	(0.014, 0.023)	(0.030, 0.045)
App. & Sec.	(0.026, 0.041)	(0.026, 0.033)	(0.026, 0.033)	(0.020, 0.029)	(0.025, 0.036)	(0.020, 0.020)
Port. Dev.	(0.021, 0.035)	(0.021, 0.031)	(0.021, 0.031)	(0.016, 0.025)	(0.020, 0.031)	(0.016, 0.028)
IoT	(0.001, 0.002)	(0.002, 0.004)	(0.002, 0.004)	(0.001, 0.003)	(0.001, 0.003)	(0.001, 0.002)
Phys. Sec.	(0.004, 0.008)	(0.004, 0.007)	(0.004, 0.007)	(0.005, 0.010)	(0.005, 0.007)	(0.005, 0.007)
Pers. Sec.	(0.002, 0.003)	(0.005, 0.008)	(0.005, 0.008)	(0.008, 0.013)	(0.004, 0.006)	(0.004, 0.006)
Priority Vector and Ranking						
	Net. & Sys.	App. & Sec.	Port. Dev.	IoT	Phys. Sec.	Pers. Sec.
Priority Vector	**(0.016, 0.024)**	(0.024, 0.031)	(0.019, 0.026)	(0.004, 0.003)	(0.005, 0.007)	(0.004, 0.006)
Rank	3	1	2	6	4	5

$\tilde{x}_{ij} = (x_{ij}^l \cdot w_j^l,\ x_{ij}^u \cdot w_j^u) = (\tilde{x}_{ij}^l,\ \tilde{x}_{ij}^u)$, where $i = 1, 2, \ldots, n$

$$\tilde{a}_{ij}^l = \frac{\tilde{x}_{ij}^l}{\sum_{i=1}^{n} x_{ij}^u} \quad ; \quad a_{ij}^u = \frac{\tilde{x}_{ij}^u}{\sum_{i=1}^{n} x_{ij}^l}$$

Example calculation for a_{12}:

$$\tilde{a}_{12}^l = (0.32 \cdot 0.117) \cdot \frac{1}{3.02} = 0.012 \quad ; \quad a_{12}^u = (0.37 \cdot 0.148) \cdot \frac{1}{2.91} = 0.019$$

The Two-Dimensional Fuzzy AHP Weight for the Comparison Between the First Criterion, 'Network and System,' and the Second Criterion, 'Application & Data Security':

$(\tilde{a}_{12}^l,\ a_{12}^u) = (0.012,\ 0.019)$

Fuzzy weight calculation:

$$\left(w_i^l = \left(\prod_{j=1}^{n} \tilde{a}_{ij}^l \right)^{1/n} \quad ; \quad w_i^u = \left(\prod_{j=1}^{n} \tilde{a}_{ij}^u \right)^{1/n} \right) = (0.016,\ 0.024)$$

Table 8: Two-Dimensional Weighted Fuzzy AHP

Within the article, it is concluded that the method applied on the digital information assets system is effective in decomposing overlapping criteria. Through the proposed process steps, it is revealed that the Application & Data Security and Portable Device & Environment criteria have different importance rankings. In multi-criteria decision problems with multiple main criteria with different number of sub-criteria, the selection process of risky digital information assets can become complicated for decision makers. Especially when there is no distinction between criteria that appear to have the same importance, organizations have difficulty in deciding which criterion to develop a prevention strategy or make a financial investment for. The proposed method determines the degree of importance between the criteria more precisely and ensures that each criterion has different weights. Thus, decision makers are provided with a more rational and prioritized evaluation opportunity and strategic planning processes become more effective. Additionally, the paper proposes to integrate the Hurwicz criterion into the OCTAVE Allegro method and transform it into a relative risk matrix to facilitate the risk assessment process. In Tables 9 and 10, the risk score of the criteria for each environmental condition is calculated and the risk score ranges are determined, and risk pools are created by ranking the importance of the criteria with high scores according to the riskiest environment. To integrate the decision maker's feelings according to the decision process into the importance values in the prioritization vector, a relative risk matrix is created by grouping the criteria according to different risk environments using Equation (11).

	$\beta = 0$	$\beta = 0{,}5$	$\beta = 1$
Networks & Systems	0,244	0,201	0,159
Application & Data Security	0,315	0,276	0,237
Portable Device & Environment	0,295	0,244	0,194
Internet of Things	0,029	0,020	0,011
Security of Physical Places	0,075	0,060	0,045
Security of Personnel	0,067	0,055	0,043

Calculation of Adjusted Fuzzy Weights Using α-Cut and β-Weighting

$G_i = \beta \cdot w_i^l + (1-\beta) \cdot w_i^u, \quad 0 \le \beta \le 1, \quad 0 \le \alpha \le 1, \quad i < j$
Given: $\alpha = 0.8$
Criterion: Network & Systems
$\beta = 0 : (0 \times 0.016) + (1-0) \times 0.024 = 0.24$
$\beta = 0{,}5 : (0.5 \times 0.016) + (1-0.5) \times 0.024 = 0.20$
$\beta = 1 : (1 \times 0.016) + (1-1) \times 0.024 = 0.16$

Table 9: The Risk Matrix for Two-Dimensional Weighted Fuzzy AHP

	0,38–0,26	0,25–0,13	0,12–0,00
$\beta = 0$	1. Application & Data Security, 2. Portable Device & Environment	3. Networks & Systems	4. Security of Physical Places, 5. Security of Personnel, 6. Internet of Things
$\beta = 0{,}5$	1. Application & Data Security	2. Portable Device & Environment, 3. Networks & Systems	4. Security of Physical Places, 5. Security of Personnel, 6. Internet of Things
$\beta = 1$		1. Application & Data Security, 2. Portable Device & Environment, 3. Networks & Systems	4. Security of Physical Places, 5. Security of Personnel, 6. Internet of Things

Table 10: The Hurwicz Risk Matrix

4. Conclusion

In multicriteria decision problems, the AHP method is used to determine criteria weights through pairwise comparisons of alternatives and criteria, and to compute and rank the alternative's relative importance. However, when dealing with uncertainty and overlapping criterion evaluations, the AHP method is insufficient. Therefore, the FAHP method is used to perform more precise evaluations under conditions of indecisiveness and uncertainty. FAHP, which expresses and calculates using triangular numbers, produces more precise, adaptable, and practical results than the classical AHP method. However, neither method is completely adequate for evaluating overlapping criterion sets. This is because both methods focus on directly converting fuzzy structures into crisp values, introducing uncertainty into the results and risk structure. Although the α-cut method is suggested in fuzzy approaches to increase the degree of crisp values representing fuzzy numbers, the decision matrix is still converted to crisp values during the processing stages, thus reducing the FAHP method back to the classical AHP method and preventing the attainment of crisp importance rankings for overlapping criteria. In this article, providing an effective method for the selection of risky criteria is based on creating a hierarchical structure by using the AHP method to ensure the consistency of the decision matrix and eliminating the fuzziness in expert opinions with FAHP. However, in case the fuzziness is insufficient in separating the conflicting criteria, it is suggested that the FAHP method is first combined with the α - alpha cut-off method to create a two-dimensional confidence interval of expert opinions. This two-dimensional confidence interval aims to provide a healthier balance between different expert opinions. The normalization process in the two-dimensional F-entropy method obtained by the alpha cut method is carried out, and also proposed to include the sub-criteria ratios as a correction factor in the calculation stages if the main criteria have different sub-criteria. In this way, the main criteria alongside the sub-criteria are effectively included in the evaluation. The integration of the correction factor into the fuzzy entropy method, which is proposed to be used in this paper, aims to eliminate the imbalances between the weights of the criteria. Thus, a more balanced risk distribution is ensured, while concurrently, criteria with different numbers of sub-criteria are prevented from being of equal importance to each other and a healthier prioritization opportunity is provided to decision makers. This approach helps to evaluate the criteria of different dimensions and scope in a balanced manner. In particular, it becomes easier for organizations to direct their limited resources to the most critical areas and risk management processes become more effective. Within the scope of this paper, it is proposed to use the two-dimensional F-entropy importance weights obtained by integrating the correction factor as the relative importance multiplier of the criteria in the two-dimensional FAHP method. In this context, overlapping criteria can be separated and the importance values of the relevant main criteria can be differentiated, allowing more precise determination of the determined importance values. The two-dimensional values of the differentiated and non-overlapping criteria were grouped according to different environmental conditions, and a risk pool was created for the criteria. The method proposed in this paper can increase the efficiency and accuracy of the evaluation process and can be an effective tool in achieving the desired goals.

Attribution

This study is derived from the implementation of the doctoral thesis currently being conducted by Aysu Yaşar at the Institute of Social Sciences, Trakya University, under the supervision of Prof. Dr. M. Kenan Terzioğlu.

References

[1] Agrawal, N., and Dixit, J. (2022). Assessment of landslide susceptibility for Meghalaya (India) using bivariate (frequency ratio and Shannon entropy) and multi-criteria decision analysis (AHP and fuzzy-AHP) models. All Earth, 34(1), 179–201. doi: 10.1080/27669645.2022.2101256

[2] Arslan, R., and Filiz, M. (2021). Veri Zarflama Analizi ve ENTROPY Temelli TOPSIS Yöntemi ile Doğu Anadolu Bölgesi Hastanelerinin Etkinlik Analizi. Artvin Çoruh Üniversitesi Uluslararası Sosyal Bilimler Dergisi, 7(1), 65–83. doi: 10.22466/acusbd.884242

[3] Buckley, J. J. (1985). Ranking alternatives using fuzzy numbers. Fuzzy Sets and Systems, 29, 145–153. doi: 10.1016/0165-0114(85)90013-2

[4] Caralli, R. A., Stevens, J. F., Young, L. R., and Wilson, W. R. (2007). Introducing octave allegro: Improving the information security risk assessment process. Software Engineering Institute, Carnegie Mellon, Hansom AFB, MA. url: https://insights.sei.cmu.edu/documents/786/2007$_{0}$05$_{0}$01$_{1}$4885*.pdf* [Accessed 09/06/25]

[5] Duleba, S., Kutlu Gündoğdu, F., and Moslem, S. (2021). Interval-Valued Spherical Fuzzy Analytic Hierarchy Process Method to Evaluate Public Transportation Development. Informatica, 32(4), 661–686. doi: 10.15388/21-INFOR451

[6] Efe, A. (2023). A comparison of key risk management frameworks: COSO-ERM, NIST RMF, ISO 31000, COBIT. Denetim ve Güvence Hizmetleri Dergisi, 3(2), 185–205. url: https://dergipark.org.tr/tr/pub/audas/issue/79262/1291915 [Accessed 09/06/25]

[7] Feizi, F., Karbalaei-Ramezanali, A., and Tusi, H. (2017). Mineral potential mapping via TOPSIS with hybrid AHP–Shannon entropy weighting of evidence. Natural Resources Research, 26, 553–570. doi: 10.1007/s11053-017-9338-3

[8] Gündoğdu, F. K., Duleba, S., Moslem, S., and Aydın, S. (2021). Evaluating public transport service quality using picture fuzzy analytic hierarchy process and linear assignment model. Applied Soft Computing, 100, 106920. doi: 10.1016/j.asoc.2020.106920

[9] Hurwicz, L. (1951). Some specification problems and applications to econometric models. Econometrica, 19(3), 343–344. url: https://www.jstor.org/stable/1907903 [Accessed 09/06/25]

[10] Karami, A., and Johansson, R. (2014). Utilization of Multi Attribute Decision Making Techniques to Integrate Automatic and Manual Ranking of Options. Journal of Information Science and Engineering, 30, 519–534. url: https://repository.uel.ac.uk/item/85x70 [Accessed 09/06/25]

[11] Kaufmann, A., and Gupta, M. M. (1988). Fuzzy Mathematical Models in Engineering and Management Science. North-Holland.

[12] Kaur, S., Singh, S., Gupta, S., and Wats, S. (2023). Risk analysis in decentralized finance (DeFi): a fuzzy-AHP approach. Risk Management, 25(2), 13. doi: 10.1057/s41283-023-00118-0

[13] Keleş, N. (2025). Measuring trade facilitation for the seven emerging economies (E7) using multi-criteria decision-making methods. Croatian Journal of Operational Research, 16(1), 17–29. doi: 10.17535/crorr.2025.0002

[14] Kumar, M., and Gupta, S. (2020). Security perception of e-banking users in India: An analytical hierarchy process. Banks and Bank Systems, 15(1), 11-20. doi: 10.21511/bbs.15(1).2020.02

[15] Lotfi, F. H., and Fallahnejad, R. (2010). Imprecise Shannon's Entropy and Multi Attribute Decision Making. Entropy, 12(1), 53–62. doi: 10.3390/e12010053

[16] Nasrullah, M., Suryawan, S. H., Istyanto, N. P., and Kristanto, T. (2022). Risk Priority Analysis for Change Management on E-Government using RIPC4 and AHP. Journal of Information Systems and Informatics, 4(1), 16–29. doi: 10.51519/journalisi.v4i1.218

[17] Randhawa, N. S., and Heady, E. O. (1963). Decision Making Under Uncertainty with Special Reference to Agriculture (In India). Indian Journal of Agricultural Economics, 18(3), 9–22. doi: 10.22004/ag.econ.231612

[18] Saaty, T. L. (1980). The Analytic Hierarchy Process: Planning, Priority Setting, Resource Allocation. McGraw-Hill, New York.

[19] Shannon, C. E. (1948). A mathematical theory of communication. The Bell System Technical Journal, 27(3), 379–423. https://people.math.harvard.edu/ ctm/home/text/others/shannon/entropy/entropy.pdf [Accessed 09/06/25]

[20] Terzioğlu, M. K., and Yaşar, A. (2022). Çok Kriterli Karar Verme Modelleri: AHP ve Bulanık AHP Yöntem Karşılaştırması. 3. Uluslararası Uygulamalı İstatistik Kongresi. url: https://www.uyik.org/uploads/uyik–2022-kongre-kitabi.pdf [Accessed 10/02/25]

[21] Yaşar, A., and Terzioğlu, M. K. (2022). Çok Kriterli Karar Verme Modellerinde AHP Yönteminin İncelenmesi. 3. Uluslararası Uygulamalı İstatistik Kongresi. url: https://www.uyik.org/uploads/uyik–2022-kongre-kitabi.pdf [Accessed 10/02/25]