Cyber Security Criteria: Fuzzy AHP approach

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Abstract

One of the main Cyber security's task is to ensure the real time protection of information and networks. In the last decade the number of cyber security attacks and its frequency has increased, creating the need for new data protection systems. In this paper we present two groups of criteria with a total of eight sub-criteria affecting cyber security, and their ranking using Fuzzy AHP. The Data/password leak, Fishing detection and DoS attack detection are recognized as the most important sub-criteria.

Keywords

cyber security, criteria, AHP, Fuzzy AHP

1. Introduction

The information is always considered as an important part in the sustainable success competitivness. The rapid development of IoT, cloud computing and data transfer, influencing the thinking of people and changing their lifestyle increase the number of exploitable vulnerabilities. To ensure real-time protection of information and information systems from intruders, organizations spent a lot of effort and resources in determining the intrusion criteria determination. The number of cybersecurity breaches over the last two decades is constantly increasing, and different approaches and techniques have been introduced by researchers and experts to implement robust security mechanisms. Defining and ranking of criteria affecting intrusion systems become challenging issue for researchers and cyber security experts often applying some of the MCDM approaches.

2. Methodology

In this section basic characteristics of triangular fuzzy numbers and phases of the Fuzzy analytic hierarchy process will be presented.

2.1. Triangular fuzzy numbers

Let all fuzzy sets defined on the set of real numbers $\mathbb{R}$ be represented as $F(\mathbb{R})$. The number $A \in F(\mathbb{R})$ is a fuzzy number if there exists $x_0 \in \mathbb{R}$ so condition $\mu_A(x_0) = 1$ holds, and $A_\lambda = \left[x, \mu_{A_\lambda}(x) \geq \lambda\right]$ is a closed interval for every $\lambda \in [0, 1]$ [1]. The membership function, a component of a triangular fuzzy number (TFN) A, is a function $\mu_A : \mathbb{R} \to [0, 1]$, defined as

$$\mu_A(x) = \begin{cases} (x-l)/(m-l), & l \leq x \leq m, \\ (u-x)/(u-m), & m \leq x \leq u, \\ 0, & \text{otherwise}, \end{cases}$$

where inequality $l \leq m \leq u$ holds. Variables l, m, and u are the lower, middle, and upper value, respectively, and when $l = m = u$, TFN becomes a crisp number. In the sequel, the triangular fuzzy number will be denoted by $\tilde{A} = (l, m, u)$.

Assume two TFNs, $\tilde{A}_1 = (l_1, m_1, u_1)$, $\tilde{A}_2 = (l_2, m_2, u_2)$, and scalar $k > 0$, $k \in \mathbb{R}$. The basic arithmetic operations (addition, subtraction, multiplication, scalar multiplication, and inverse element) are respectively defined as follows [2, 3]:

$$\begin{aligned} \tilde{A}_1 \oplus \tilde{A}_2 &= (l_1, m_1, u_1) \oplus (l_2, m_2, u_2) \\ &= (l_1 + l_2, m_1 + m_2, u_1 + u_2), \\ \tilde{A}_1 \ominus \tilde{A}_2 &= (l_1, m_1, u_1) \ominus (l_2, m_2, u_2) \\ &= (l_1 - u_2, m_1 - m_2, u_1 - l_2), \\ \tilde{A}_1 \otimes \tilde{A}_2 &= (l_1, m_1, u_1) \otimes (l_2, m_2, u_2) \\ &= (l_1 \cdot l_2, m_1 \cdot m_2, u_1 \cdot u_2), \\ k \cdot \tilde{A}_1 &= k \cdot (l_1, m_1, u_1) = (k \cdot l_1, k \cdot m_1, k \cdot u_1), \\ \tilde{A}_1^{-1} &= (l_1, m_1, u_1)^{-1} = (1/u_1, 1/m_1, 1/l_1). \end{aligned} \tag{1}$$

BISEC'22: 13th International Conference on Business Information Security, December 03, 2022, Belgrade, Serbia
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For a given triangular number $\tilde{A} = (l, m, u)$ the left side of the membership function $\mu_{\tilde{A}}$ and it's inverse are given as

$$\mu^l_{\tilde{A}} = (x - l)/(m - l);\ (\mu^l_{\tilde{A}})^{-1} \\ = l + (m - l)y, y \in [0, 1], \tag{2}$$

and the right side of the membership function $\mu_{\tilde{A}}$ and it's inverse are given as

$$\mu^r_{\tilde{A}} = (u - x)/(u - m);\ (\mu^r_{\tilde{A}})^{-1} \\ = u + (m - u)y, y \in [0, 1]. \tag{3}$$

The total integral value, according to [4] as a combination of left and right integral values $I_L(\tilde{A})$ and $I_R(\tilde{A})$, is

$$\begin{aligned} I^\lambda_T(\tilde{A}) &= \lambda I_R(\tilde{A}) + (1 - \lambda)I_L(\tilde{A}) \\ &= \lambda \int_0^1 (\mu^r_{\tilde{A}})^{-1} dy + (1 - \lambda) \int_0^1 (\mu^l_{\tilde{A}})^{-1} dy \\ &= \frac{1}{2} (\lambda u + m + (1 - \lambda)l) . \end{aligned} \tag{4}$$

where λ represents an optimism index. The optimistic ($\lambda = 1$), balanced ($\lambda = 0.5$) and pessimistic ($\lambda = 0$) point of view are significant to obtain and rank criteria, while semi-pessimistic ($\lambda = 0.25$) and semi-optimistic ($\lambda = 0.75$) point of view are used when additional opinion is needed or more accurate results required [5].

2.2. Fuzzy AHP

Since its creation [6], the Analytic Hierarchy Process (AHP) had a respectable application in MCDM, enabling the decision makers to solve complex problems by decomposing them into a hierarchical structure, creating the comparison matrix and determining the importance of one indicator above others. The specified level of uncertainty of a team of experts (or even one expert) [7] due to the inability to express the significance of some criteria has led to the introduction of Fuzzy AHP [8, 9] enabling conversion of linguistic statements into mathematical expressions.

The phases in FAHP can be summarized as follows [1, 10]:

Phase I: Establishing the hierarchy
In general, the hierarchical structure has been organized vertically: the main goal is, as the most important component, at the top; the criteria that contribute to the goal are at the intermediate levels; and the sub-criteria are at the lowest level.

Phase II: Matrix comparison
Determining the pairwise comparison matrix $\widetilde{D}$ in terms of TFNs. In this step, a positive fuzzy reciprocal comparison matrix $\widetilde{D} = (\tilde{d}_{ij})_{n\times n}$ with a total of $n(n-1)/2$ comparisons of elements from a higher level with elements from a lower level is developed. The fuzzy value $\tilde{d}_{ij}$ represents the degree of relative importance between criteria; $i = j$, $\tilde{d}_{ij} = (1, 1, 1)$, and $\tilde{d}_{ij} = 1/\tilde{d}_{ji}$, otherwise.

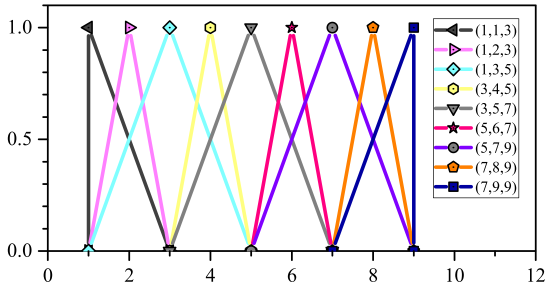

Figure 1: Graphic representation of triangular fuzzy numbers.

Table 1 shows the fuzzy scale for constructing pairwise comparisons.

As it was recommended in [11], a fuzzy distance of 2 and odd values as boundaries for all non-intermediate values are applied in order to achieve better consistency. There are also different scales of triangular fuzzy numbers applicable in the previous case [12, 13].

The graphic representation of the used FAHP scale with all three values (lower, median, and upper) is presented in Figure 1.

Phase III: Matrix consistency review
For a matrix $D = (d_{ij})_{n\times n}$, the consistency index CI and consistency ratio CR are calculated using equations

$$CI = \frac{\lambda_{max} - n}{n - 1}, \quad CR = \frac{CI}{RI}, \tag{5}$$

where $\lambda_{\max}$ corresponds to a maximal eigenvalue of matrices D and RI is a random index, as shown in Table 2. The RI values for matrices of dimensions of one and two are equal to zero.

The value $CR < 0.1$ confirms the comparison matrix consistency, while otherwise the reason for inconsistency should be found and calculations repeated [14].

Phase IV: The fuzzification phase
Using the triangular fuzzy numbers from the comparison matrix $\widetilde{D} = \left(\tilde{d}_{ij}\right)_{n\times n}$, applying

$$A = \sum_{i=1}^{n} \sum_{j=1}^{n} \tilde{d}_{ij} = \sum_{i=1}^{n} \sum_{j=1}^{n} \left(l_{ij}, m_{ij}, u_{ij}\right), \tag{6}$$

and

Table 1
Linguistic terms, and denotation of TFNs and inverse TFNs.

Linguistic Term	Denotation of TFNs	TFNs	Denotation of inverse TFNs	Inverse TFNs
Equal importance	$\tilde{1}$	$(1, 1, 3)$	$\tilde{1}^{-1}$	$(1/3, 1, 1)$
Absolutely weak dominance	$\tilde{2}$	$(1, 2, 3)$	$\tilde{2}^{-1}$	$(1/3, 1/2, 1)$
Extremely weak dominance	$\tilde{3}$	$(1, 3, 5)$	$\tilde{3}^{-1}$	$(1/5, 1/3, 1)$
Very weak dominance	$\tilde{4}$	$(3, 4, 5)$	$\tilde{4}^{-1}$	$(1/5, 1/4, 1/3)$
Fairly weak dominance	$\tilde{5}$	$(3, 5, 7)$	$\tilde{5}^{-1}$	$(1/7, 1/5, 1/3)$
Fairly strong dominance	$\tilde{6}$	$(5, 6, 7)$	$\tilde{6}^{-1}$	$(1/7, 1/6, 1/5)$
Very strong dominance	$\tilde{7}$	$(5, 7, 9)$	$\tilde{7}^{-1}$	$(1/9, 1/7, 1/5)$
Extremely strong dominance	$\tilde{8}$	$(7, 8, 9)$	$\tilde{8}^{-1}$	$(1/9, 1/8, 1/7)$
Absolutely strong dominance	$\tilde{9}$	$(7, 9, 9)$	$\tilde{9}^{-1}$	$(1/9, 1/9, 1/7)$

Table 2
The table of Random Index numbers.

Matrix Dimension	Three	Four	Five	Six	Seven	Eight	Nine	Ten
RI	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

$$\begin{aligned} A^{-1} &= \left(\sum_{i=1}^{n}\sum_{j=1}^{n}\tilde{d}_{ij}\right)^{-1} \\ &= \left(\left(\sum_{i=1}^{n}\sum_{j=1}^{n}l_{ij}\right)^{-1}, \left(\sum_{i=1}^{n}\sum_{j=1}^{n}m_{ij}\right)^{-1}\right. \\ &\left., \left(\sum_{i=1}^{n}\sum_{j=1}^{n}u_{ij}\right)^{-1}\right) \end{aligned} \tag{7}$$

the value of the fuzzy synthetic extent is obtained as follows [3]:

$$\begin{aligned} \widetilde{S}_i &= \sum_{j=1}^{n}\tilde{d}_{ij} \otimes A^{-1} \\ &= \sum_{j=1}^{n}(l_{ij}, m_{ij}, u_{ij}) \otimes A^{-1}, \quad i = \overline{1,n}. \end{aligned} \tag{8}$$

Phase V: The defuzzification phase
The defuzzification phase starts with the weighted vector w_i in order to obtain the total integral value for the TFNs, $\widetilde{S}_i$ [15]

$$\begin{aligned} w_i &= I_T^{\lambda}(\widetilde{S}_i) = \frac{1}{2}\big(\lambda u_i + m_i + (1-\lambda)m_i\big), \\ &\lambda \in [0,1], i = \overline{1,n}, \end{aligned} \tag{9}$$

Phase VI: Normalization phase
In the normalization phase, the weight vectors w_i^* for criteria are obtained.

$$w_i^* = \frac{w_i}{\sum_{i=1}^{n} w_i} \tag{10}$$

Phase VII: Ranking phase
The weights for each sub-criterion are obtained by multiplying the weights of the criteria and sub-criteria. Then, arranging the obtained weights, the sub-criteria ranking is received.

3. Literature preview and Cyber security criteria

In this section the literature preview of security indicators followed by selected criteria will be given.

The internet changed the concept of computing as we know it, enlarging the number of possibilities and opportunities, which lead to the higher number of risks, possible vulnerabilities and system breakthroughs. Computer security primarily focuses on protecting a specific source or valuable data and information within a single computer device. Security is defined as the reaction taken to security threats resulting from a harmful act by some people [16]. AHP and its various generalizations (MCDM approaches) offer a lot of potential in the process of solving hierarchical decision-making problems. Since Saaty proposed it, AHP method was used to calculate the weights of criteria significantly advancing this

Table 3
Fuzzy comparison matrix and weights for criteria X1 (CR=0.04402465).

X1	X11	X12	X13	X14	AHP	FAHP		
						λ = 0	λ = 0.5	λ = 1
X11	$\tilde{1}$	$\tilde{3}$	$\tilde{4}$	$\tilde{5}$	0.530599135	0.477368222	0.477024348	0.476868011
X12	$\tilde{3}^{-1}$	$\tilde{1}$	$\tilde{2}$	$\tilde{4}$	0.244465446	0.281716383	0.271062766	0.266219241
X13	$\tilde{4}^{-1}$	$\tilde{2}^{-1}$	$\tilde{1}$	$\tilde{3}$	0.153145735	0.167372164	0.181500963	0.187924431
X14	$\tilde{5}^{-1}$	$\tilde{4}^{-1}$	$\tilde{3}^{-1}$	$\tilde{1}$	0.071789684	0.073543231	0.070411923	0.068988316

Table 4
Fuzzy comparison matrix and weights for criteria X2 (CR=0.007825137).

X2	X21	X22	X23	X24	AHP	FAHP		
						λ = 0	λ = 0.5	λ = 1
X21	$\tilde{1}$	$\tilde{2}$	$\tilde{3}$	$\tilde{5}$	0.475835435	0.432258637	0.450646573	0.458890834
X22	$\tilde{2}^{-1}$	$\tilde{1}$	$\tilde{2}$	$\tilde{4}$	0.288398487	0.319466591	0.302417953	0.294774169
X23	$\tilde{3}^{-1}$	$\tilde{2}^{-1}$	$\tilde{1}$	$\tilde{2}$	0.154445145	0.159447146	0.165605041	0.168365944
X24	$\tilde{5}^{-1}$	$\tilde{4}^{-1}$	$\tilde{2}^{-1}$	$\tilde{1}$	0.081320933	0.088827626	0.081330432	0.077969053

process in finding the decision that best matches given conditions. Some of the recent publications regarding security criteria are published by Almotiri [17] exploring the effectiveness of malicious traffic detention systems, Goutam et al [18] established techniques for identifying shortcoming of online applications, Agarwal et al tested university's software security using ANP-TOPSIS evaluation [19]. The AHP-TOPSIS based approach dealed with healthcare electronic service quality making the interactivity, service correctness, and responsiveness the most important characteristics in providing satisfying and effective healthcare web services was presented in [20], while in [21] using the same methodology under hesitant fuzzy conditions Sahu presented a novel framework for software durability assessment. Alharbe [22] also used MCDM approaches in recognizing and prioritizing usable security attributes while designing and developing the software, and in [23] authors determined and prioritized confidence parameters in fog computing.

In the sequel we present criteria and sub-criteria related to cyber secutity.

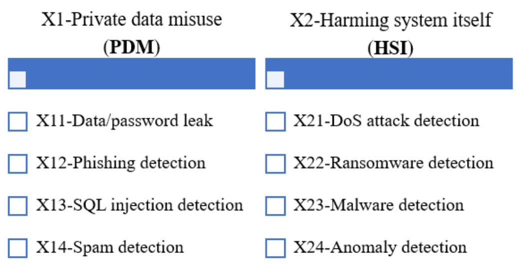

Figure 2: Criteria and sub-criteria for cyber security.

4. Results and conclusion

Applying the AHP and the FAHP method presented in previous section, ranking of main criteria is obtained. The pairwise comparison matrix for main criteria is consistent since $CR = 0$. Obtained weights $w(X1) = 0.666666667$ and $w(X2) = 0.333333333$ in the case of AHP and $w(X1) = 0.787234043, w(X2) = 0.212765957$ for $\lambda = 0$, $w(X1) = 0.800928022, w(X2) = 0.199071978$ for $\lambda = 0.5$, and $w(X1) = 0.810638298, w(X2) = 0.189361702$ for $\lambda = 1$ in the case of three points of view in the FAHP case correspond to the main criteria *Private data misuse* and *Harming system itself* respectively. The results of sub-criteria corresponding to *PDM* group are presented in Table 3. In both AHP and all three FAHP cases, sub-criteria *X11-Data/password leak* ranked highest, while criteria *X14-Spam detection* ranked lowest. This is comprehensible since regular users, as well as big systems and corporations are more susceptible to data attacks, which corresponds to results presented in [24]. The highest ranked sub-criteria in *PDM* group is approximately 7.39 times higher than lowest ranked sub-criteria in the AHP case, and 6.77 higher in the balanced FAHP case.

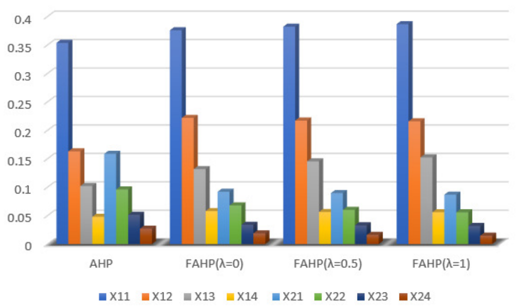

Figure 3: Sub-criteria final ranking.

Sub-criteria *X21-DoS attack detection* representing opportunity for interrupting the functioning of the system and system resource access for its users has the highest rank with the weight vector $w(X21) = 0.475835435$ in the AHP case and median vector for all three FAHP cases $w(X2) = 0.447265348$, followed by sub-criteria *X22-Ransomware detection*, $w(X22)_{AHP} = 0.288398487$ and $w(X22)_{FAHP(median)} = 0.305552904$. *X23-Malware detection*, being a coded file that is spread by cyber-attackers through different messaging systems requiring the victim to execute it and making damage in the system is ranked third in all observed cases. *Anomaly detection*, the sub-criteria *X24* is on the bottom of the ladder having 5.85 times lowest rank than the *X21* in the AHP case, and the 5.89 lowest rank in the optimistic FAHP case. All of these sub-criteria belong to the *HSI* group and the rankin result can be seen in Table 4. The final ranking of sub-criteria is obtained multiplying the weights of main criteria by in-group sub-criteria weights. As it was presented in Figure 3, the sub-criteria from *X1*, namely *X11* and *X12* are ranked first and second in AHP and all FAHP cases, while *X13* and*X14* ranked fourth and seventh in the AHP, and third and sixth (fifth) in the pessimistic and balanced (optimistic) point of view in the FAHP case. The fourth and seventh rank of sub-criteria *X21* and *X23* is valid for all FAHP cases, while sub-criteria *X24* lies at the bottom of the ladder for both, AHP and FAHP cases.

Acknowledgments

This paper was supported in part by the Blockchain Technology Laboratory at Belgrade Metropolitan University, Belgrade, Serbia and in part by the Serbian Ministry of Education, Science and Technological Development through Mathematical Institute of the Serbian Academy of Sciences and Arts.

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