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Threat Evaluation In Air Defense Systems Using Analytic Network Process[1]

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1 Introduction

Decision-making in a stressful environment is a hard task for human beings. It requires strong mental capability and years of experience. Air defense decision-making is a highly complex process and it can only be performed by experienced and skilled experts in the field.

Informally, the purpose of Threat Evaluation (TE) is to rank observed enemy craft according to their threatening behavior with respect to a number of Defended Assets (DAs). In theory, it is evident that the TE process provides decision support (which improves command and control as well as situation awareness) and is dedicated to improving the operational tempo of operators.

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The motivation behind this study is the need for a decision tool, which takes environmental weapon and threat related- characteristics into account, and suggests an effective course of action for air defense in a complex attack environment. Unlike former studies, which proposed mainly heuristic algorithms for threat evaluation phase, we use Analytic Network Process (ANP) for calculating threat values of targets. Those studies will be mentioned in detail in the next section of the study.

The originality of the work comes from the proposed network-based model for TE which considers relations between parameters and produces a final threat value for targets. Our method is based on different aircraft types and we evaluate them according to their technical specifications, behaviors and arrival times to certain points in a number of scenarios.

The remaining part of the paper is organized as follows: a brief overview of literature and the problem's definition are given in Section 2. Since the TE and weapon assignment problems have been studied to great extent, the most relevant works are mentioned only. A short description of ANP and applied work examples are given in Section 3. In section 4, decision making model developed for the problem is defined and the established method is tested on a scenario and quality of acquired solutions are reviewed in section 5. Finally, Section 6 concludes the work by discussing the proposed method for TE process and suggests future work.

2 Threat Evaluation Concept

During this decision process, there are some elements of surface-to-air defense such as DAs, threat elements and weapon systems which are needed to be considered according to their attributes:

- Defended Assets: In defensive counter-air operations, a listing of those assets from the critical asset list prioritized by the Command and Control (C2) center to be defended with the resources available. Thus, some of the DAs have higher priority than the others and need better protection.

- Threat Elements: Generally, in air defense, threat means all enemy forces attempting to attack or penetrate the friendly air environment. In other words, threats are elements with the intention of damage or injury to the DAs. Threat can be missiles (ballistic, guided. etc.) or aircrafts which drop bombs or fires directly to the ground targets.
- Weapon Systems: Weapons such as Anti-aircraft (AA) guns or Surface-to-air missiles (SAM) are used in air defense to eliminate targets.

2.1 *Threat Evaluation*

TE is a pre-deployment process by which a commander and his staff draw on their encyclopedic knowledge of the enemy, including doctrine, tactics and capabilities, to deduce the nature of the threat they face.

Many methods were studied for assessment of threats. Liebhaber and Smith investigated the cognitive aspect of the concept.[2] Bayesian network is used in a basic form by Endsley[3], Okello and Thoms[4] improved the application and Johansson and Falkman[5] applied a scenario and reported the results. Jan[6] introduced a modified probabilistic neural network (MPNN) that can achieve classification, target threat level assessment method based on genetic neural network to estimate the threat level of aerial targets is proposed by Chen and Zhang[7], Azak and Bayrak[8] described details of

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[2] M. J. Liebhaber and C. A. Smith, "Naval Air Defense Threat Assessment: Cognitive Factors and Model," in *Command and Control Research and Technology Symposium* (San Diego CA: Pacific Science and Engineering Group Inc., 2000).
[3] Mica R. Endsley, "Toward a Theory of Situation Awareness in Dynamic Systems," *Human Factors: The Journal of the Human Factors and Ergonomics Society* 37, no. 1 (1995): pp. 32-64.
[4] N. Okello and G. Thorns, "Threat Assessment Using Bayesian Networks," in *Proceedings of the Sixth International Conference of Information Fusion* 2, (2003): pp. 1102-1109.
[5] F. Johansson and G. Falkman. "A Bayesian Network Approach to Threat Evaluation with Application to an Air Defense Scenario," in *11th International Conference on Information Fusion* (2008): pp. 1-7.
[6] T. Jan, "Neural Network Based Threat Assessment for Automated Visual Surveillance," in *Proceedings of the IEEE International Joint Conference on Neural Networks* 2, 2 (2004): pp. 1309-1312.
[7] Chen Hua and Zhang Ke, "Target Threat Assessment Based on Genetic Neural Network," in *International Conference on Industrial Control and Electronics Engineering (ICICEE)*, 2012, pp. 1789-1792.

threat evaluation and weapon allocation system project in the scope of machine learning techniques. Changwen and You[9] used Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). Liang[10] examined the use of a fuzzy knowledge-based system in assisting naval operators in managing the situation and threat assessment problem in a littoral environment, a reasoning system for threat assessment (TA) is investigated based on intuitionistic fuzzy logic by Dongfeng et al.[11] and a fuzzy rule-based inference method is proposed by Choi et al..[12] Lozano et al.[13] combined the other famous multi-criteria decision making methods, Analytic Hierarchy Process (AHP) and TOPSIS with fuzzy logic to evaluate the alternative military training aircrafts. Game theory is another method used recently by Paulson et al.[14]. Their model assumes that attacker has all the information of defender's resource allocation and applies a multi-attribute utility model depending on the information about threat and weapon.

[8] M. Azak and A. E. Bayrak, "A New Approach for Threat Evaluation and Weapon Assignment Problem, Hybrid Learning with Multi-Agent Coordination," in *23rd International Symposium on Computer and Information Sciences (ISCIS)*, 2008, pp. 1-6.

[9] Changwen Qu and You He, "A Method of Threat Assessment Using Multiple Attribute Decision Making," in *6th International Conference on Signal Processing* 2, 2 (2002): pp. 1091-1095.

[10] Liang Yawei, "An Approximate Reasoning Model for Situation and Threat Assessment," in *Fourth International Conference on Fuzzy Systems and Knowledge Discovery*, 4 (2007):, pp. 246-250.

[11] Chen Dongfeng, Feng Yu and Liu Yongxue, "Threat Assessment for Air Defense Operations Based on Intuitionistic Fuzzy Logic," *Procedia Engineering* 29, no. 0 (2012): pp 3302-3306.

[12] Byeong Ju Choi, Ji Eun Kim, Jin Soo Kim and Chang Ouk Kim, "Fuzzy Rule-Based Method for Air Threat Evaluation," *Journal of the Korea Institute of Military Science and Technology* 19, no. 1 (2016): pp. 57-65.

[13] J. M. Sánchez-Lozano, J. Serna and A. Dolón-Payán, "Evaluating Military Training Aircrafts through the Combination of Multi-Criteria Decision Making Processes with Fuzzy Logic. A Case Study in the Spanish Air Force Academy," *Aerospace Science and Technology* 42, (2015): pp. 58-65.

[14] Elisabeth C. Paulson, Igor Linkov and Jeffrey M. Keisler, "A Game Theoretic Model for Resource Allocation among Countermeasures with Multiple Attributes," *European Journal of Operational Research* 252, no. 2 (2016): pp. 610-622.

Three main criteria of TE process are *Capability*, *Intent*[15] and *Proximity*[16]:

- *Capability:* It refers to the identification of threat and its ability to destroy or cause damage to the DAs. Radar cross-section, answer to identification friend or foe (IFF) interrogation, etc. can give us information about target's identity. The capability of a target depends on its platform capability whether, for example, it can maneuver fast or is a stealth platform and on the weapons it carries for the mission. Fuel capacity of a target is another parameter that can give us information about target's maximum range of operation. Basically, first the target must be identified; then its capability can be inferred.

- *Intent:* Unlike capability, intent is rather subjective term in TE process. Intent refers to the assumed future behavior of a target. Knowing the intent of a target is essential for an operator to prioritize its processing and to choose suitable tactics and appropriate weapons to engage the target. Target intent is one of the main discriminators for classifying whether a target is friend or foe since a particular type of aircraft may be in service in both forces. For example, typical commercial aircrafts tend to fly with steady speed, constant altitude and in a straight line. If a given target candidate maneuvers more than what is considered "normal", this would be an indicator of threat compare to a non-maneuvering target. Other indications of hostile intent may be the use of radar-jamming units or whether the target's fire control radar is on.

- *Proximity:* Proximity is a class of parameters that are measuring the target's proximity to the DA. One of the most important parameter to define the distance of target to the DA is the Closest Point of Approach, (CPA). CPA is the point where the distance between asset and the direction of velocity of target will be the shortest (Fig. 1). CPA can easily be used as a measure of threat level. Targets in far distances can be considered less threatening, while targets in shorter distances indicate more potential threat.

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[15] D. Hall and J. Llinas, *Handbook of Multisensor Data Fusion: Theory and Practice*, Second Editio n (US:CRC Press, 2008).

[16] Jean Roy, Stephane Paradis and Mohamad Allouche, "Threat Evaluation for Impact Assessment in Situation Analysis Systems," in *Signal Processing, Sensor Fusion, and Target Recognition* XI, 4729 (2002): pp. 329-341.

Given n possible threats and m DAs, some of the parameters related to the CPA are:

Time to CPA (TCPA): Target's approaching time to the CPA calculated using the following formula:

$$TCPA_{ij} = \frac{d(CPA_{ij})}{v_i} \quad \forall i = 1, \dots, n \quad \forall j = 1, \dots m \tag{1}$$

Where $d(CPA_{ij})$ represents the distance of target i to CPA of DA_j and v_i is the speed of target i.

CPA in Units of Time (CPAIUOT): Means the time it takes the target to hit the DA after arriving the CPA calculated using the following formula:

$$CPAIUOT_{ij} = \frac{d(dCPA_{ij})}{v_i} \quad \forall i = 1, \dots, n \quad \forall j = 1, \dots m \tag{2}$$

Where $d(dCPA_{ij})$ represents the distance of target i to DA_j after arriving CPA.

Time Before Hit (TBH): TBH is an estimate of the time it takes the target to hit or reach the DA calculated using the following:

$$TBH_{ij} = TCPA_{ij} + CPAIUOT_{ij} = \frac{d(CPA_{ij}) + d(dCPA_{ij})}{v_i} \quad \forall i = 1, \dots, n \quad \forall j = 1, \dots m \tag{3}$$

These calculations are made under the assumption of constant target velocities. This is a reasonable assumption for many platforms and conventional weapons, since they seldom make rapid maneuvers between two track updates.[17]

[17] M. G. Oxenham, "Enhancing Situation Awareness for Air Defence Via Automated Threat Analysis," in Proceedings of the Sixth International Conference of Information Fusion, 2 (2003): pp. 1086-1093.

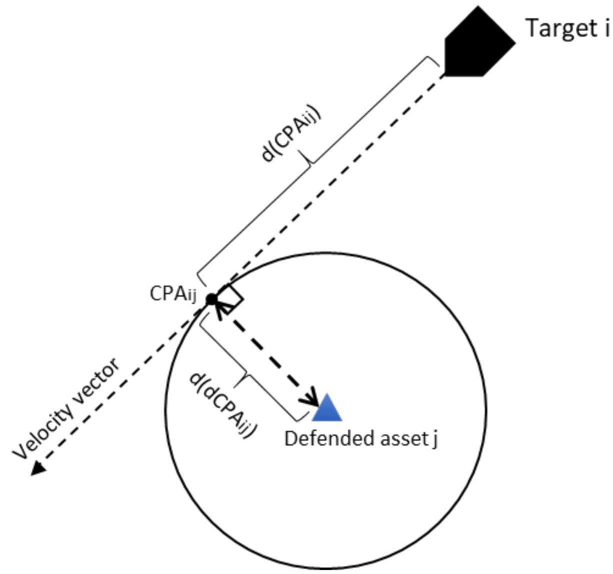

Figure 1: Closest Point of Approach

2.2 *Problem Definition*

The main aim of air defense is to defend the assets by using weapons to neutralize the threats. Threats are generally airplanes flying at very high speeds. They send rockets to or drop bombs onto assets. During the engagement period, radars supply information to C2 center on velocity, position and type of threats. C2 center checks the weapon availability, decides on the best engagement strategy and sends engagement orders to weapons. If the weapon accepts the order, it prepares to fire.

In the beginning of the process, we need to determine the intent of the possible threats whether they have hostile intent or they are neutral. Then we may treat them as targets and assign their target values. To do so, some parameters about threats considering their past and present conditions need to be gathered. The parameters are listed below:

- Altitude (ALT): Approximate feet above ground or an indication of change (e.g. climbing).

- Countermeasures (CM): Using techniques or tools to avoid radar signals, thermal or infrared guided systems.
- Heading: Exact compass heading or indication of heading relative to the DA (i.e. opening or closing).
- Closest Point of Approach (CPA): Estimated distance that track will pass by own ship if the track and own ship remain on their current courses.
- Fire Control Radar (FCR): A system that is used by an attacker to track a target by intense radio beams.
- Flight Plan/Airlane: A published or otherwise known commercial air route.
- Maneuverability (MNB): Agility of track and maneuver capacity
- Maximum Radius of Operation (MRO): Also varies according to platform type and fuel capacity, indicates maximum reach point of track beginning from lift-off.
- Origin (ORG): Indicates the country from which the track most likely originated.
- Platform Weapons (PW): Armaments on track.
- Speed (SPD): Approximate airspeed or an indication of change (e.g. increasing).
- Weapon Engagement Range (WER): Varies for the onboard armament, indicates maximum and minimum firing distances.

2.3 *Intent Estimation*

Usually, intent of a target cannot be observed directly; but what can be observed are the signs whether the enemy is engaged in particular actions or behavior. Therefore, to read the intent of a target, operators get as many clues as possible from different information sources such as radar, IFF-interrogation, intelligence, visual inspection, etc.

Generally a number of sequential activities are carried out within the overall task. Consider the activities of an operator from "initial detection" to "intent assessment" of a single target. The activities include recognition that the target exists, assessment of the environment in which the target is operating, and assessment of the target behavior within the environment, leading to an assumption about its intentions. A conclusion about the intent of a target may lead to actions of further investigation or to intercepting and neutralizing the target.[18]

3 Analytic Network Process – *ANP*

3.1 *General Information*

ANP is a generalization of Saaty's Analytical Hierarchy Process (AHP), which is one of the most widely used multi-criteria decision support tools.[19] ANP and its supermatrix technique can be considered as an extension of AHP that can handle a more complex decision structure, as the ANP framework has the flexibility to consider more complex inter-relationships (outer-dependence) among different elements.

ANP has a wide range of applications in the literature. The subject is still quite recent, thus, studies continues increasing in many fields. Shankar et al. proposed a combination of balanced scorecard and ANP-based approach which provides a representation of the problem for conducting reverse logistics operations for EOL computers.[20] Chung et al. proposed an application of the ANP for the selection of product mix for efficient manufacturing in a semiconductor fabricator.[21] They presented a hierarchical network model based on various factors and the interactions of factors to

[18] X. T. Nguyen, "Threat Assessment in Tactical Airborne Environments," in *Proceedings of the Fifth International Conference on Information Fusion* 2, 2 (2002): pp. 1300-1307.
[19] T.L. Saaty, *Decision Making with Dependence and Feedback: The Analytic Network Process: The Organization and Prioritization of Complexity* (US: Rws Publications, 2001).
[20] V. Ravi, R. Shankar and M. K. Tiwari, "Analyzing Alternatives in Reverse Logistics for End-of-Life Computers: Anp and Balanced Scorecard Approach," *Computers & Industrial Engineering* 48, no. 2 (2005): pp. 327-356.
[21] S. H. Chung, A. H. I. Lee and W. L. Pearn, "Analytic Network Process (Anp) Approach for Product Mix Planning in Semiconductor Fabricator," *International Journal of Production Economics* 96, no. 1 (2005): pp. 15-36.

evaluate different product mixes. Gencer and Gurpinar[22] considered supplier selection as a multi criteria decision problem. A solution based on a combined ANP and DEMATEL approach to help companies that need to evaluate and select knowledge management strategies is proposed by Wu[23]. Khan and Faisal[24] presented an evaluation method that can aid decision makers in a local civic body to prioritize and select appropriate municipal solid waste disposal methods. They introduced a hierarchical network decision structure and apply the ANP super-matrix approach to measure the relative desirability of disposal alternatives using value judgments as the input of the various stakeholders. Demirtas and Ustun[25] presented a multi-period inventory lot sizing scenario, where there is single product and multiple suppliers and they suggested ANP by considering multi-period planning horizon. A multi-criteria approach to evaluate employee performance has been proposed by Gurbuz.[26] Since the employees' performance depends on various criteria simultaneously and those criteria may have interaction, choquet Integral has been used to handle this situation. Lee et al.[27] provided the first analysis on the interactive relationships among the factors in incorporating the method of ANP to simplify the process of equity investment. Tzeng and Wang[28] utilized the MCDM model combining DEMATEL with ANP and VIKOR methods to clarify the interrelated relationships of brand marketing and find the problems or gaps; then, evaluated the situation to reduce the gaps in order to achieve the aspired levels and rank the priorities in brand marketing strategies, they also

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[22] C. Gencer and D. Gurpinar, "Analytic Network Process in Supplier Selection: A Case Study in an Electronic Firm," *Applied Mathematical Modelling* 31, no. 11 (2007): pp. 2475-2486.

[23] W.W. Wu, "Choosing Knowledge Management Strategies by Using a Combined Anp and Dematel Approach," *Expert Systems with Applications* 35, no. 3 (2008): pp. 828-835.

[24] S. Khan and M. N. Faisal, "An Analytic Network Process Model for Municipal Solid Waste Disposal Options," *Waste Management* 28, no. 9 (2008): pp. 1500-1508.

[25] E. A. Demirtas and O. Ustun, "Analytic Network Process and Multi-Period Goal Programming Integration in Purchasing Decisions," *Computers & Industrial Engineering* 56, no. 2 (2009): pp. 677-690.

[26] T. Gürbüz, "Multiple Criteria Human Performance Evaluation Using Choquet Integral," *International Journal of Computational Intelligence Systems* 3, no. 3 (2010): pp. 290-300.

[27] W. S. Lee, A. Y. Huang, Y. Y. Chang and C. M. Cheng, "Analysis of Decision Making Factors for Equity Investment by Dematel and Analytic Network Process," *Expert Systems with Applications* 38, no. 7 (2011): pp. 8375-8383.

[28] Y. L. Wang and G. H. Tzeng, "Brand Marketing for Creating Brand Value Based on a Mcdm Model Combining Dematel with Anp and Vikor Methods," *Expert Systems with Applications* 39, no. 5 (2012): pp. 5600-5615.

evaluated the customer's satisfaction of brand marketing by three electronic manufacturing companies in Taiwan. Tavana et al.[29] proposed a novel analytical framework for social media platform selection which integrates the ANP with fuzzy set theory and the complex proportional assessment of alternatives with grey relations method. A maximum eigenvalue threshold as the consistency index for the ANP in risk assessment and decision analysis is proposed by Ergu et al..[30]

ANP, incorporates both qualitative and quantitative approaches to a decision problem.[31] It is also capable of capturing the tangible and intangible aspects of relative criteria that have some bearing on the decision making process.[32] Also, ANP can deal with interconnections and inner-dependence between decision factors in the same level.

3.2 *Pairwise Comparison*

Pairwise comparison is the process of comparing a set of elements, two by two, with respect to one control criterion in order to obtain those elements relative priorities again with respect to that control criterion. Generally in AHP/ANP this process is used for the followings:

- Obtain relative priorities of criteria with respect to the objective.
- Obtain relative priorities of sub-criteria with respect to the criterion they belong to.
- Evaluate alternatives with respect to subjective criteria, i.e. criteria whose values are qualitative and therefore given using linguistic terms instead of quantitative values. In other words: transform linguistic preferences or values into numbers.

[29] M.Tavana, , E. Momeni, N. Rezaeiniya, S. M. Mirhedayatian and H. Rezaeiniya, "A Novel Hybrid Social Media Platform Selection Model Using Fuzzy Anp and Copras-G," *Expert Systems with Applications* 40, no. 14 (2013): pp. 5694-5702.

[30] D. Ergu, G. Kou, Y. Shi and Y. Shi, "Analytic Network Process in Risk Assessment and Decision Analysis," *Computers & Operations Research* 42, (2014): pp. 58-74.

[31] E. Cheng and H. Li, "Analytic Network Process Applied to Project Selection," *Journal of Construction Engineering and Management* 131, no. 4 (2005): pp. 459-466.

[32] T.L. Saaty, *Decision Making with Dependence and Feedback: The Analytic Network Process: The Organization and Prioritization of Complexity* (US: Rws Publications, 2001).

- Determine the relative strength of effects for factors effecting one given factor.

A pairwise comparison matrix (A) is formed to perform this process. Let n be the number of elements to be compared with respect to one given control criterion. Then A is going to be as follows:

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix} \text{ where } a_{ij} = {}^{1}/_{a_{ji}} \text{ and } a_{ii} = 1 \quad \forall i, j = 1, \dots, n \tag{4}$$

There are various methods to retrieve weights/relative priorities from this comparison matrix. One of these methods is by using the following formula which basically takes the arithmetic average of the rows after column normalization has been performed:

$$w_i = \sum_{j=1}^{n} \left[a_{ij} \Big/ \sum_{k=1}^{n} a_{kj} \right] \Big/ n \quad \forall i = 1, \dots, n \tag{5}$$

Once the set of weights are calculated, in order for them to be used in the remaining part of the process depends on the consistency of the judgments collected in matrix A. Therefore, a consistency analysis should be performed each time one confronts a pairwise comparison matrix. As this is a very common step of a very broadly used method, for the sake of brief presentation of the topic, the reader is invited to look at Saaty's work for further details.

3.3 *A Step by Step ANP Procedure*

The outline of ANP steps as follows:

- Describe the decision problem in detail with objectives, criteria, sub-criteria.

- Determine the general network of clusters (problem's criteria) and the nodes (sub-criteria) within the clusters.
- Determine all the inter and inner-dependencies that exist among problem's criteria. After this step, the network of the decision problem will also be found.
- Build the supermatrix by performing the pairwise comparisons (as explained in Section 3.2), prioritization and define the weights of the criteria and the sub-criteria while considering the inter-dependencies between them.
- Perform pairwise comparison on clusters (as explained in Section 3.2). The derived weights will be used to find the weighted supermatrix.
- Perform consistency analysis of all the pairwise comparisons, made by the experts or decision makers, in order to make the necessary changes if there is any inconsistency above the allowed limit.
- Rate the alternatives according all the criteria and sub-criteria.
- Find the weighted supermatrix.
- Compute and find the limit supermatrix from which the overall score for the alternatives is retrieved and make the final decision as to choose the best alternative or to obtain the final ranking of the alternatives.

4 Proposed Model

4.1 *Intent Estimation Model*

Our Intent Estimation model is mainly based on a logical approach by using a series of Yes/No questions. The clues checked by this series of question are going to point out the possible intent of the flying object. Following clues are considered for the intent estimation purpose and the logical approach is given in Fig.1:

- Heading,

- Known or agreed flight plan,
- Platform type,
- Fire control radar,
- Countermeasures.

These clues are chosen based on visibility, measurability and detectability by sensors or radars in a state of area scanning (Fig. 2).

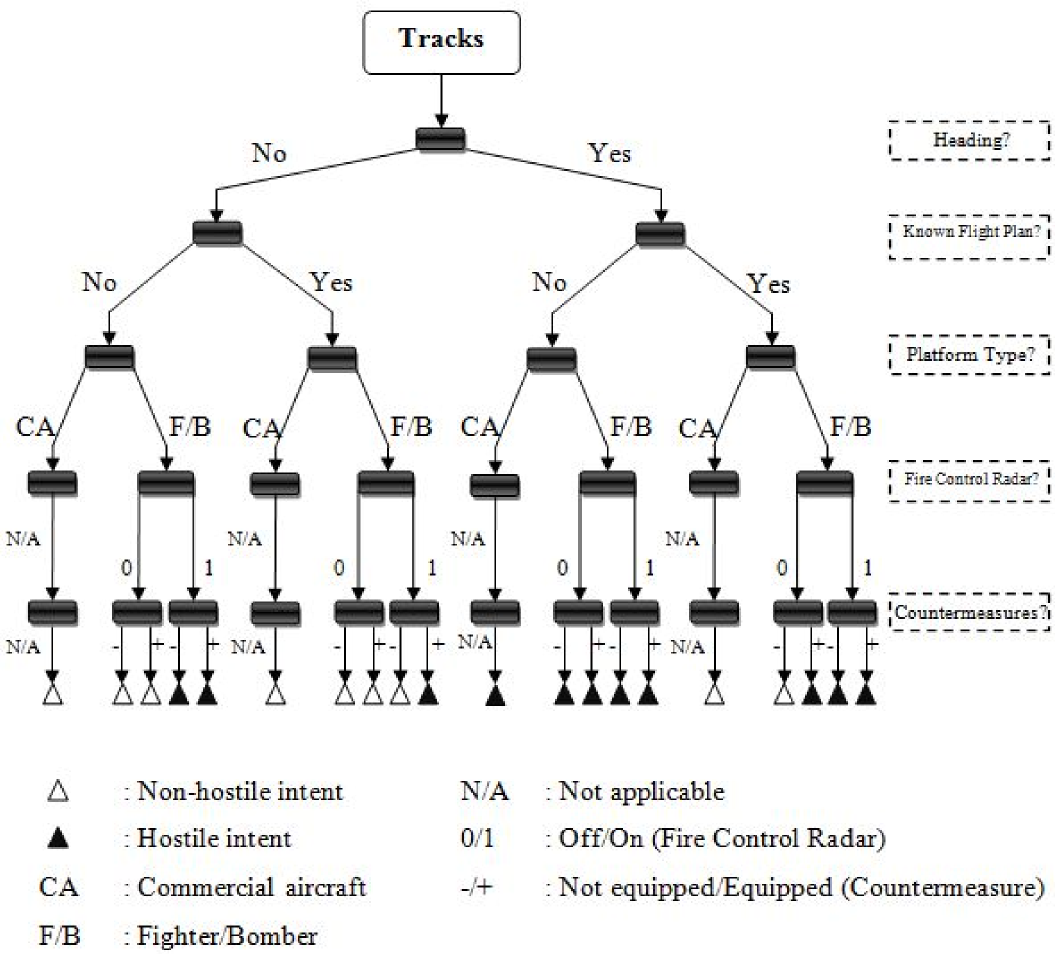

Figure 2: Intent estimation model

4.2 *Threat Evaluation Model*

Our objective for this model is to assign threat values to the detected targets regarding their hostile intents. The main function of this process is to generate values which are designed to be used as a sequencing factor or to set priorities for the targets.

It is crucial that the threat posed by a target is known before engagement in order to not waste precious time and resources on weak targets while more dangerous and powerful targets attempt successful attacks on DAs.

We design the model using Saaty's ANP to consider the existing relations between parameters and inner-dependences if there are any (Fig. 3).

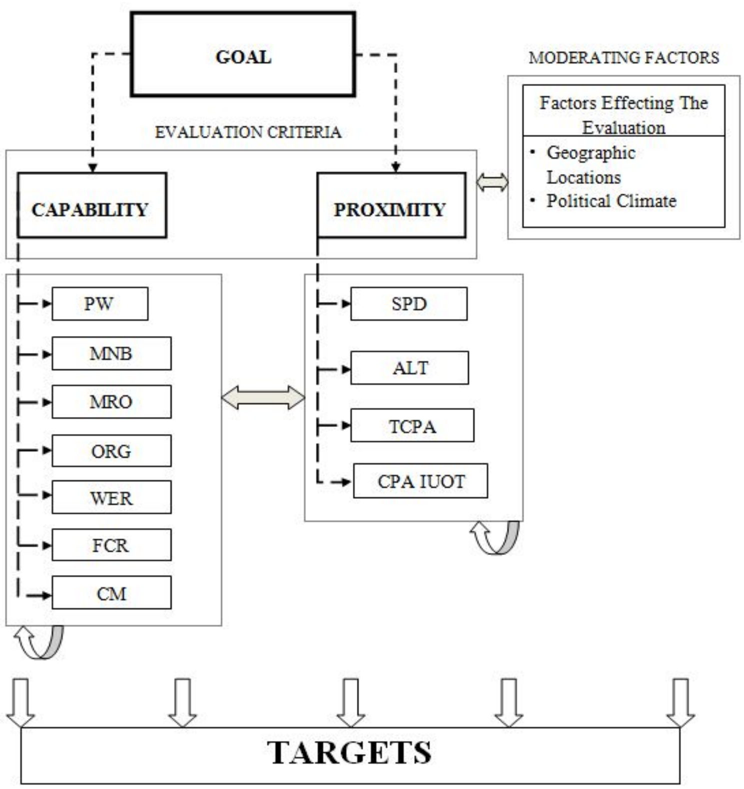

Figure 3: Threat evaluation model

4.3 *Moderating Factors*

As it can be seen in Fig.3, in addition to criteria, there are some factors that affect the parameters indirectly or cause assigning more weight on some criteria. Because of their indirect impacts, they are called as "Moderating Factors" and two moderating factors have been taken into consideration:

- *Political Climate (PC):* It corresponds to diplomatic relations between nations. When a target detected by the early warning systems, if the origin of target is known, it automatically affects the threat level of target as a result of diplomatic stage between two sides.
- *Geographic Locations (GL):* Both in defense and offense strategies, the surface features of the area have an important role. The attack plans and formations are directed while geographic obstacles and flying distances are taken into consideration.

4.4 *Relations between Criteria*

In a general context, all the criteria are affected by each other to some degree. There are direct connections between some parameters caused by kinematic effects. To illustrate this, the SPD at which an aircraft is capable of its maximum aerodynamic maneuverability is known as the corner airspeed; at any greater SPD the control surfaces cannot operate at maximum effect due to either airframe stresses or induced instability from turbulent airflow over the control surface. At lower SPDs the redirection of air over control surfaces, and thus the force applied to maneuver the aircraft, is reduced below the airframe's maximum capacity and thus the aircraft will not turn at its maximum rate.[33]

[33] B. Gal-Or, *Vectored Propulsion, Supermaneuverability, and Robot Aircraft* (New York: Springer-Verlag, 1990).

To set another example, an aircraft with more and heavier ordnance or PW will have a smaller combat radius (MRO) than the same one with less and lighter ordnance, due to higher fuel consumption at heavier weights.[34]

The number of examples can be increased but to summarize, there are relations between criteria to some level and these relations are weighted with respect to their degree of interference.

Under the lights of previously mentioned details of the evaluation process, our network is as it can be seen on the following figure:

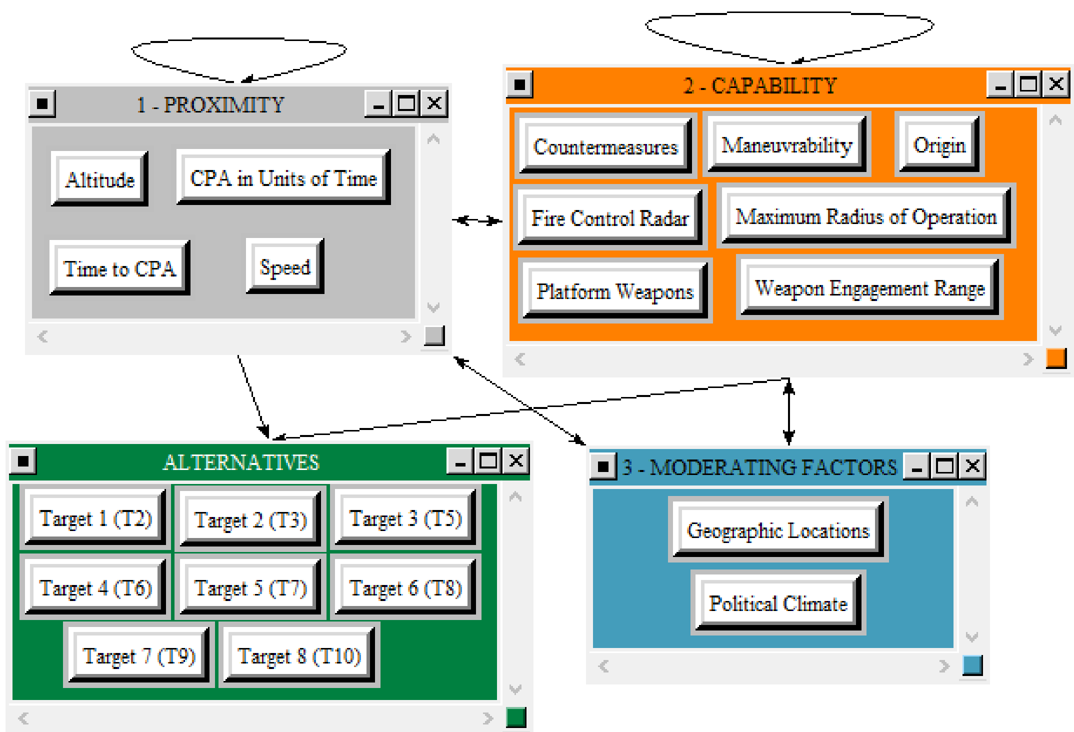

Figure 4: Evaluation model's Network (SuperDecisions Sowftware)

34 G.J.J. Ruijgrok, *Elements of Airplane Performance* (Amsterdam: Delft University Press, 1990).

5 Application

5.1 *Scenario Assumptions*

In this section, our objective is to create a scenario to test our model and later, evaluate and interpret the results. There will be 10 detected tracks and one DA in the test model as listed in Table 1. According to the scenario, our radar systems detect these tracks with their velocity vectors traverse into or pass nearby our national air space (Fig. 5). Some of these tracks will target our DA and approach it from different directions.

Table 1: List of detected tracks

	Heading	Known Flight Plan	Platform Type	Fire Control Radar	Countermeasures	INTENT
Track 1 (Tr1)	No	Yes	CA	0	Negative	Non-Hostile
Track 2 (Tr2)	Yes	No	F	1	Positive	Hostile
Track 3 (Tr3)	Yes	No	F	0	Positive	Hostile
Track 4 (Tr4)	No	No	CA	0	Negative	Non-Hostile
Track 5 (Tr5)	Yes	No	B	1	Positive	Hostile
Track 6 (Tr6)	Yes	No	B	1	Positive	Hostile
Track 7 (Tr7)	Yes	No	CA	0	Negative	Hostile
Track 8 (Tr8)	Yes	No	CA	0	Negative	Hostile
Track 9 (Tr9)	Yes	No	F	1	Positive	Hostile
Track 10 (Tr10)	Yes	No	F	1	Positive	Hostile

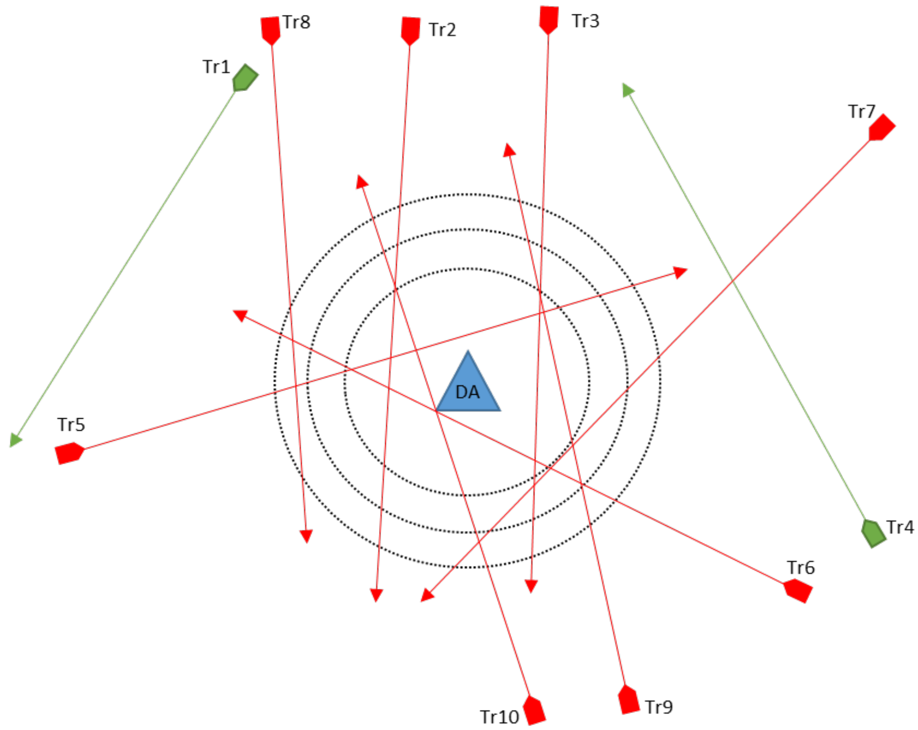

Figure 5: An illustration of the scenario

Some assumptions are made at this point in order to standardize the input data and simplify the evaluation process. They are listed below:

- All commercial aircrafts have the same specifications.
- The input data for ALT, SPD, TCPA, CPA IUOT, ORG, FCR and CM are randomly generated while the data for PW, MNB, MRO and WER are assumed as maximized based on aircraft specifications.
- The defending side has borders with attacking sides and the aircrafts are detected out of the borders of defending side.
- Commercial aircrafts with unknown flight plans are assumed to be an element of the side which they are detected within.

- ORG values of the attacking sides are evaluated by percentage, 0% being enemies while 100% being allies.

After estimating the intent of detected tracks, the ones with hostile intent are taken into consideration as targets. To evaluate these targets using ANP, we need to obtain data to assign to the parameters and use them in the model. Detecting and tracking systems obtain these data and C2 center processes them in a usable form. Some parameters are connected directly to each other. For example, if an aircraft is identified as brand name and model, then its armament and specifications of these armaments such as weight, firing range, blast radius etc. can be retrieved from database.

As presented in Table 2, in this scenario, after identifying the attackers, we extract the data of platform weapons, maneuverability (which is calculated by using thrust-to-weight ratio of aircraft), maximum radius of operation, weapon engagement range from database by reason of these aircrafts have certain specifications and they may vary in an insignificant rate.

Table 2: Target parameters in a single stage

Target No (T#)	Track No (Tr#)	ALT (m)	SPD (Km/h)	TCPA (mins)	CPA IUOT (mins)	PW (kg)	MNB (t/w)	MRO (Km)	ORG	WER (Km)	FCR	CM
T1	Tr2	8700	1080	31	3	1816	1,15	2900	1	15	0	1
T2	Tr3	14000	1360	16	5	900	1,09	3000	3	28	0	0
T3	Tr5	8000	850	28	1	8460	0,68	1100	1	10	1	1
T4	Tr6	6500	780	23	1	8460	0,68	1100	2	10	1	0
T5	Tr7	8700	910	48	20	0	0,15	7500	3	0	0	0
T6	Tr8	8230	780	52	24	0	0,15	7500	1	0	0	0
T7	Tr9	7000	885	18	4	900	1,09	3000	2	28	0	1
T8	Tr10	13000	1110	19	1	1816	1,15	2900	3	15	1	1

This scenario is based on the aerial attack examples in the past and reformed with the consultation of field experts. Attacking aircraft types and models are selected according to their availability and commonness. As a result, specifications of these aircrafts are well-defined, well-known and can be obtained easily.

Three different countries are designated as the origins of the targets. The relationships between the defending country and these three countries are scaled as percentage and 100% shows good relationships while 0% corresponds to absolute hostility. The relations between defending country and attacking countries are 50%, 30% and 80% for country A, B and C, respectively.

5.2 *Computations*

Using the relative importance vectors obtained from the cluster comparison matrices, the cluster matrix – which will be used to normalize the unweighted supermatrix – is formed as shown below in Table 3.

Table 3: Cluster matrix

	Proximity	Capability	Moderating Factors	Alternatives
Proximity	0.619	0.235	0.333	0
Capability	0.275	0.655	0.667	0
Moderating Factors	0.074	0.081	0	0
Alternatives	0.031	0.028	0	0

Node comparisons provide the unweighted supermatrix given in Appendix A. Limiting powers of weighted supermatrix (can be seen in Appendix B) will generate the final priorities of all sub-criteria which can be observed in Table 4.

Table 4: Relative priorities of criteria

	Normalized By Cluster	Limiting
Altitude	0,2571	0,1316
CPA in Units of Time	0,2053	0,1051
Speed	0,3717	0,1902
Time to CPA	0,1659	0,0849
Countermeasures	0,0242	0,0097
Fire Control Radar	0,0848	0,0339
Maneuvrability	0,0819	0,0327
Maximum Radius of Operation	0,0528	0,0211
Origin	0,2969	0,1186
Platform Weapons	0,3549	0,1418
Weapon Engagement Range	0,1045	0,0418
Geographic Locations	0,5267	0,0467
Political Climate	0,4733	0,0420

5.3 *Results*

After arranging the relations between criteria, the collected data are used in our ANP model and final target values are obtained as in Table 5. According to these target values, Target 4 has the highest priority among all other targets. The final values of the targets are as follows:

T4 > T3 > T8 > T7 > T2 > T1 > T6 > T5

Table 5: Calculated target values

Alternatives	Normal	Ideal	Ranking
T1 (Tr2)	0.1138	0.6153	6
T2 (Tr3)	0.1168	0.6316	5
T3 (Tr5)	0.1656	0.8957	2
T4 (Tr6)	0.1849	1.0000	1
T5 (Tr7)	0.0686	0.3708	8
T6 (Tr8)	0.0776	0.4199	7
T7 (Tr9)	0.1326	0.7173	4
T8 (Tr10)	0.1401	0.7577	3

Apparently PW and SPD are the most relatively important criteria, because the reason Target 4 has the highest value is that it has the highest values in PW while in other criteria, it has the lowest values generally. Similarly, Target 5 has the lowest value by being a CA and despite both Target 5 and Target 6 have approximate values, their difference in ORG values caused them to differentiate.

6 Conclusions

Calculations and results obtained here are provided by SuperDecisions software. Once the network has been built and the comparisons have been performed, the results are generated in an insignificant time interval (less than 1 second). However, since this is not an optimization problem but rather a problem of threat value generation for the hostile alternatives, the process does not require a comparison of the computation times. Rather, what is important here is the perspective that the method and the model brings to the field.

Many methods are used in threat evaluation concept in the past studies. As of today, our literature research showed a set of methods used in this field. Namely: Bayesian networks, neural networks, machine learning, TOPSIS, fuzzy rule based systems, AHP and game theory. Saaty's Analytic Network Process has not been used yet in the field and so we applied this method in order to

- extend the past studies,
- define the relations between parameters more thoroughly and
- bring a new perspective to the TE field.

First of all, ANP is a MCDM technique which acknowledges the interactions of decision criteria. This fundamentally separates current study and all the remaining MCDM applications performed in this field because of the fact that the ones used beforehand are the ones which ignores those interactions by their definition. Therefore all the details that have been missed by the simplification of the network structure towards having a hierarchical structure (as used in AHP and TOPSIS for example) are now under consideration. From this perspective, in terms of MCDM, ANP is certainly better able to capture the complexity of the situation without having the need to make assumptions like the independence of the criteria. The only cost of the positive addition of its use brings is the time spent for the building of the model and pairwise comparisons. But once this model is built and the comparisons for the criteria have been performed, the model will be used as it is for other scenarios in the same manner. Therefore the only change will be on the basis of the hostile vessels. Final computations with the software are not at all time consuming as stated before. One must note that the software used in order to solve the model is freeware.

Considering the promising results that are obtained, it can be said that ANP can be a preferable method for this concept. After that, these values can be easily integrated into the Weapon Assignment process in both static and dynamic form as further studies.

As to the limitations of the proposed model, due to the fact that it is an expert system, it relies highly on experts' judgments and hence, bounded rationality conditions, as in all expert systems, apply also for the proposed method. The decision problem here represents quite crucial situations where lives, values (for instance historical), intel etc. are at stake. Therefore, experts' experience and ability to assess and synthesize military and technical as well as political data is highly important. On the other hand, other than the alternatives or the locations being scenario specific, for a country, "political climate" is quite dynamic and therefore contains a high uncertainty level even if the scenario remains the same. This in turn will of course not prevent to reach a reasonable solution but the perfect information conditions will not be available for the time being.

Our main objective in this study is first to eliminate targets that do not pose a threat and then evaluate real threats by generating their threat value. Intent estimation is the first step we take in this process. Intent estimation model in this study is based on observations and eliminations and used for determining actual targets. Then these actual targets are evaluated via our ANP model.

Future research can include:

- Automation of this proposed model. A machine learning process based on this research could bring new horizons to the field; which in turn bring their own concerns both ethical (as the ones in automated cars) and security (such as ploys).
- Fuzzy extensions of the proposed model as experts' opinion can be quite vague. To see, if any, the difference of final evaluations could also help the previously mentioned future research.

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APPENDIX A:

Table 6: Unweighted SuperMatrix

Table 6. Unweighted SuperMatrix

	ALT	CPAIUT	SPD	TCPA	CM	FCR	MNB	MRO	ORG	PT	WER	GL	PL	Tr2	Tr3	Tr5	Tr6	Tr7	Tr8	Tr9	Tr10
ALT	0	0,2	0,2	0,3333	0	0,333	0,2	1	0,333	0,113	0,333	1	1	0	0	0	0	0	0	0	0
CPAIUT	0,4	0	0,4	0	0	0	0	0	0	0,652	0	0	0	0	0	0	0	0	0	0	0
SPD	0,2	0,8	0	0,6667	0	0,667	0,8	0	0,667	0,235	0,667	0	0	0	0	0	0	0	0	0	0
TCPA	0,4	0	0,4	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CM	0	0	0	0	0	0	0	0	0	0	0	0,2	0,111	0	0	0	0	0	0	0	0
FCR	0	0	0	0	0	0	0	0	0	0,352	0	0	0	0	0	0	0	0	0	0	0
MNB	0	0,06667	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MRO	0,086	0	0,143	0	0	0	0,072	0	0	0,089	0	0	0	0	0	0	0	0	0	0	0
ORG	0	0	0	0	0	0	0,534	0,1	0	0,559	0	0,8	0,889	0	0	0	0	0	0	0	0
PT	0,706	0,46667	0,857	0	0	0,2	0,393	0,9	0	0	1	0	0	0	0	0	0	0	0	0	0
WER	0,208	0,46667	0	0	0	0,8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
GL	1	0,9	0,9	0,8889	1	0	1	1	0	0,2	0,8	0	0	0	0	0	0	0	0	0	0
PL	0	0,1	0,1	0,1111	0	0	0	0	1	0,8	0,2	0	0	0	0	0	0	0	0	0	0
Tr2	0,117	0,08605	0,139	0,1001	0,249	0,001	0,187	0,1	0,122	0,081	0,142	0	0	0	0	0	0	0	0	0	0
Tr3	0,189	0,05143	0,176	0,1936	0,001	0,001	0,177	0,104	0,076	0,04	0,263	0	0	0	0	0	0	0	0	0	0
Tr5	0,108	0,25816	0,109	0,1113	0,249	0,332	0,111	0,038	0,122	0,378	0,094	0	0	0	0	0	0	0	0	0	0
Tr6	0,088	0,25816	0,101	0,1347	0,001	0,332	0,111	0,038	0,203	0,378	0,094	0	0	0	0	0	0	0	0	0	0
Tr7	0,117	0,01286	0,117	0,0646	0,001	0,001	0,024	0,259	0,076	0,001	0,001	0	0	0	0	0	0	0	0	0	0
Tr8	0,111	0,01088	0,101	0,0599	0,001	0,001	0,024	0,259	0,122	0,001	0,001	0	0	0	0	0	0	0	0	0	0
Tr9	0,094	0,06429	0,114	0,1721	0,249	0,001	0,177	0,104	0,203	0,04	0,263	0	0	0	0	0	0	0	0	0	0
Tr10	0,175	0,25816	0,143	0,1637	0,249	0,332	0,187	0,1	0,076	0,081	0,142	0	0	0	0	0	0	0	0	0	0

APPENDIX B:

Table 7: Weighted SuperMatrix

Table 7. Weighted SuperMatrix

	ALT	CPAIUT	SPD	TCPA	CM	FCR	MNB	MRO	ORG	PT	WER	GL	PL	Tr2	Tr3	Tr5	Tr6	Tr7	Tr8	Tr9	Tr10
ALT	0	0,1239	0,124	0,2065	0	0,0853	0,0471	0	0,2276	0,0266	0,0784	0	0	0	0	0	0	0	0	0	0
CPAIUT	0,248	0	0,248	0	0	0	0	0	0	0,1534	0	0	0	0	0	0	0	0	0	0	0
SPD	0,124	0,49559	0	0,413	0	0,1707	0,1882	0	0,4553	0,0553	0,1569	0	0	0	0	0	0	0	0	0	0
TCPA	0,248	0	0,248	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CM	0	0	0	0	0	0	0	0	0	0	0	0,133	0,074	0	0	0	0	0	0	0	0
FCR	0	0	0	0	0	0	0	0	0	0,2308	0	0	0	0	0	0	0	0	0	0	0
MNB	0	0,01834	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MRO	0,024	0	0,039	0	0	0	0,0475	0	0	0,0582	0	0	0	0	0	0	0	0	0	0	0
ORG	0	0	0	0	0	0	0,35	0,0656	0	0,3664	0	0,533	0,593	0	0	0	0	0	0	0	0
PT	0,194	0,12835	0,236	0	0	0,1426	0,2579	0,5899	0	0	1	0	0	0	0	0	0	0	0	0	0
WER	0,057	0,12835	0	0	0	0,5705	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
GL	0	0,06664	0,067	0,0658	0	0	0	0	0	0,0162	0,0647	0	0	0	0	0	0	0	0	0	0
PL	0	0,00741	0,007	0,0082	0	0	0	0	0	0,0647	0,0162	0	0	0	0	0	0	0	0	0	0
Tr2	0,004	0,0027	0,004	0,0032	0,0071	3E-05	0,0053	0,0028	0,0101	0,0023	0,004	0	0	0	0	0	0	0	0	0	0
Tr3	0,006	0,00162	0,006	0,0061	3E-05	3E-05	0,005	0,003	0,0063	0,0011	0,0075	0	0	0	0	0	0	0	0	0	0
Tr5	0,003	0,00812	0,003	0,0035	0,0071	0,0103	0,0032	0,0011	0,0101	0,0107	0,0027	0	0	0	0	0	0	0	0	0	0
Tr6	0,003	0,00812	0,003	0,0042	3E-05	0,0103	0,0032	0,0011	0,0168	0,0107	0,0027	0	0	0	0	0	0	0	0	0	0
Tr7	0,004	0,0004	0,004	0,002	3E-05	3E-05	0,0007	0,0074	0,0063	3E-05	3E-05	0	0	0	0	0	0	0	0	0	0
Tr8	0,003	0,00034	0,003	0,0019	3E-05	3E-05	0,0007	0,0074	0,0101	3E-05	3E-05	0	0	0	0	0	0	0	0	0	0
Tr9	0,003	0,00202	0,004	0,0054	0,0071	3E-05	0,005	0,003	0,0168	0,0011	0,0075	0	0	0	0	0	0	0	0	0	0
Tr10	0,006	0,00812	0,004	0,0052	0,0071	0,0103	0,0053	0,0028	0,0063	0,0023	0,004	0	0	0	0	0	0	0	0	0	0