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Solution Of (2×N) And (N×2) Fuzzy Game Problem By Graphical Method Using Hexagonal Fuzzy Numbers

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Abstract:
In this research paper, we present a comprehensive study on the solution of (2xn) and (nx2) fuzzy game problems using the graphical method, where the payoffs are represented by Hexagonal Fuzzy Numbers (HFNs). Hexagonal fuzzy numbers are particularly effective in modeling uncertainty due to their flexibility and ability to represent a wider range of imprecision compared to triangular and trapezoidal fuzzy numbers.
The primary objective of this study is to develop a systematic and efficient approach for solving two-person zero-sum fuzzy games with rectangular payoff matrices of order (2xn) and (nx2). The proposed methodology begins with the formulation of the fuzzy payoff matrix using hexagonal fuzzy numbers. To facilitate comparison and optimization, an appropriate ranking function is employed to convert hexagonal fuzzy payoffs into crisp equivalents without significant loss of information. This transformation enables the application of the graphical method, which is particularly suitable for solving games involving two strategies for one of the players.
The study demonstrates that the graphical method remains simple, intuitive, and computationally efficient even when extended to fuzzy environments with hexagonal fuzzy payoffs. Few illustrative examples are included to validate the proposed approach and to highlight its applicability in decision-making problems. The proposed framework enhances the analytical capability of fuzzy game theory and offers a practical solution technique for complex decision-making problems under uncertainty.

Key Word:*Fuzzy Numbers; Hexagonal Fuzzy Number; Fuzzy Game Problem; Graphical Method.*

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I. Introduction

Game theory is a fundamental mathematical framework for analyzing strategic interactions among rational decision-makers and has been extensively applied in economics, operations research, management science, and engineering disciplines. In the classical formulation of two-person zero-sum games, payoff values are assumed to be precise and deterministic. However, such an assumption is often unrealistic in practical decision-making environments, where uncertainty, vagueness, and incomplete information are inherent. To overcome these limitations, fuzzy set theory, introduced by Zadeh [13], has been effectively incorporated into game theory, leading to the development of fuzzy game theory [13,14].

In fuzzy game problems, payoff values are represented by fuzzy numbers, enabling a more realistic modeling of uncertainty arising from subjective judgments, estimation errors, and fluctuating system parameters. Various forms of fuzzy numbers—such as triangular, trapezoidal, and pentagonal fuzzy numbers have been widely employed in the existing literature for solving fuzzy games [4,5]. In recent years, hexagonal fuzzy numbers (HFNs) have attracted increasing attention due to their enhanced capability to represent uncertainty with greater flexibility and precision, as they allow a more refined description of the membership function compared to simpler fuzzy number representations.

Among two-person zero-sum games, (2×n) and (n×2) games occupy a prominent position because of their frequent occurrence in real-world applications and their amenability to graphical solution techniques. The graphical method is a well-established approach for solving such games, particularly when one of the players has exactly two pure strategies. Several researchers have investigated the application of graphical methods to fuzzy game problems using different types of fuzzy numbers. However, studies focusing on the solution of (2×n) and (n×2) fuzzy games using hexagonal fuzzy numbers remain relatively limited.

In this paper, we propose a systematic approach for solving (2×n) and (n×2) fuzzy game problems using the graphical method, where the payoff matrix entries are represented by hexagonal fuzzy numbers. The proposed methodology employs an appropriate ranking technique to transform fuzzy payoffs into comparable scalar values, enabling the application of graphical analysis. The optimal mixed strategies for both players and the fuzzy value of the game are obtained accordingly.

II. Preliminaries

Fuzzy Set

Let X be a non-empty set. A fuzzy set "A" in X is characterized by its membership function A: X $\longrightarrow$ [0, 1] and A(x) is interpreted as the degree of membership of element x in fuzzy A for each x Ɛ X. Complete non-membership is represented by the value zero; complete participation is represented by the value one and intermediate degrees of membership are represented by values in between. The membership function of fuzzy set A is also known as the mapping A.

Fuzzy Number

A fuzzy number "A" is a convex normalized fuzzy set on the real line R, such that:
(a) There exists at least one $x_\circ$ Ɛ R with μ_A (x)= 1
(b) μ_A (x) is piecewise continuous.

Hexagonal Fuzzy Numbers [10,11]

A fuzzy number is hexagonal fuzzy number denoted by $\tilde{A}_H=(a_1,a_2,a_3,a_4,a_5,a_6)$ where a_1,a_2,a_3,a_4,a_5,a_6 are real numbers and its membership function $\mu_{\tilde{A}H}$ is given below,

$$\mu_{\tilde{A}H}(x) = \begin{cases} 0 & ; \text{for } x<a_1 \\ \frac{1(x-a1)}{2(a2-a1)} & ; \text{for } a_1 \le x \le a_2 \\ \frac{1}{2}+\frac{1(x-a2)}{2(a3-a2)} & ; \text{for } a_2 \le x \le a_3 \\ 1 & ; \text{for } a_3 \le x \le a_4 \\ 1-\frac{1(x-a4)}{2(a5-a4)} & ; \text{for } a_4 \le x \le a_5 \\ \frac{1(a6-x)}{2(a6-a5)} & ; \text{for } a_5 \le x \le a_6 \\ 0 & ; \text{for } x>a_6 \end{cases}$$

Parameteric Form Of Hexagonal Fuzzy Numbers

A hexagonal fuzzy number denoted by $\tilde{A}$ is defined as $\tilde{A}_w$= ($P_1(u)$, $Q_1(v)$, $Q_2(v)$, $P_2(u)$) for u Ɛ [0,0.5] and v Ɛ[0.5,w] where,
(a) P_1 (u) is a bounded left continuous non-decreasing function over [0,0.5].
(b) Q_1 (v) is a bounded left continuous non-decreasing function over [0.5,w].
(c) Q_2 (v) is a bounded left continuous non-increasing function over [w,0.5].
(d) P_2 (u) is a bounded left continuous non-increasing function over [0.5,0].

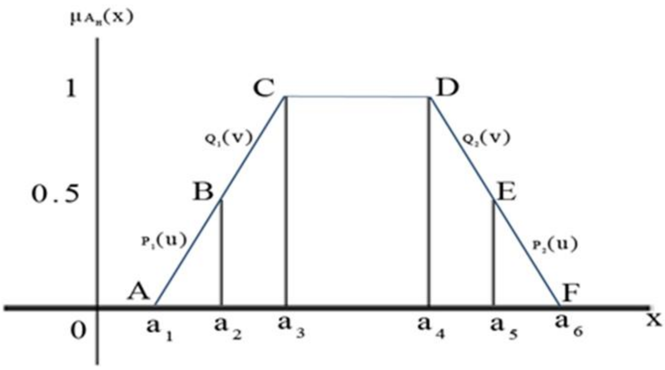

Figure No 1: Graphical Representation of a normal hexagonal fuzzy number for x Ɛ [0,1].

Alpha Cut

The classical set $\tilde{A}_\alpha$ called the α-cut set is the set of elements whose degree of membership in $\tilde{A}_H=(a_1,a_2,a_3,a_4,a_5,a_6)$ is no less than α, it is defined as
$\tilde{A}_\alpha = \{ x \text{ Ɛ } X / \mu_{\tilde{A}H} \ge \alpha\}$

$$= \begin{cases} [P_1(\alpha), P_2(\alpha)] & \text{for } \alpha \in [0,0.5] \\ [Q_1(\alpha), Q_2(\alpha)] & \text{for } \alpha \in [0.5, 1] \end{cases}$$

Alpha Cut of a normal Hexagonal Fuzzy Number

The α-cut of a normal hexagonal fuzzy number $\tilde{A}_H=(a_1,a_2,a_3,a_4,a_5,a_6)$ is given by the definition i.e. w=1 for all $\alpha \in [0,1]$ is

$$\tilde{A}_\alpha = \begin{cases} [2\alpha(a_2-a_1)+a_1,\ -2\alpha(a_6-a_5)+a_6] & \text{for } \alpha \in [0,0.5] \\ [2\alpha(a_3-a_2)-a_3+2a_2,\ -2(a_5-a_4)+2a_5-a_4] & \text{for } \alpha \in [0.5,1] \end{cases}$$

Ranking of Hexagonal Fuzzy Numbers

The measure of a hexagonal fuzzy number is obtained by the average of two fuzzy side areas, left side area and the right side area, from membership function to α-axis.

Let Ã be a normal hexagonal fuzzy number. The value $M_\circ^{hex}(\tilde{A})$, called the measure of Ã is calculated as follows,

$$M_\circ^{hex}(\tilde{A}) = \frac{3\sqrt{3}}{4}[(a_1+a_3+a_6)(k)+(a_2+a_4+a_5)(1-k)]; \text{ where } 0 \le k \le 1$$

III.Solution Of All (2×N) And (N×2) Matrix Games

Consider the general game matrices

Case: 1

$$\mathbf{A} = \begin{pmatrix} a_{11} & a_{12} & a_{13} & \dots & \dots & \dots & a_{1n} \\ a_{21} & a_{22} & a_{23} & \dots & \dots & \dots & a_{2n} \end{pmatrix}$$

Case: 2

$$\mathbf{A} = \begin{pmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \\ a_{31} & a_{32} \\ \vdots & \vdots \\ a_{n1} & a_{n2} \end{pmatrix}$$

Algorithm

1. First we shall convert the given fuzzy game problem into a crisp value problem and calculate the value of $M_\circ^{hex}(a_{ij})$.

2. Check for the saddle point in the payoff matrix.

3. If there is no saddle point, reduce the given matrix using graphical method. Write the payoff equations and plot them on a graph.

4. After plotting the graph mark the max-min or min-max point. Now the game is reduced to 2×2 matrix. For this payoff matrix find the optional strategies of Players A and B.

Note: We shall consider Case:1 in Example 1 and Case:2 in Example 2.

Example 1:

Consider the following fuzzy game problem

$$\mathbf{P_A} \overset{\mathbf{P_B}}{\begin{pmatrix} (2,4,6,8,-5,-1) & (0,1,2,3,4,6) & (-3,-2,2,3,4,6) & (0,2,4,6,-7,-3) & (0,1,2,3,8,10) \\ (-8,-7,4,6,7,10) & (-2,-1,0,1,4,6) & (-6,-5,6,8,0,3) & (-4,-3,8,10,2,5) & (-4,-3,1,2,3,5) \end{pmatrix}}$$

Where P_A denotes Player A and P_B denotes Player B.

Solution: By the definition of hexagonal fuzzy numbers Ã is calculated as

$$M_\circ^{hex}(\tilde{A}) = \frac{3\sqrt{3}}{4}[(a_1+a_3+a_6)(k) + (a_2+a_4+a_5)(1-k)]$$

Step: 1 Change the given fuzzy problem into a crisp value problem. Here the value of k = 0.6,

Table No 1: Shows the crisp values of the hexagonal fuzzy numbers in Example 1.

a_{11}=(2, 4, 6, 8,-5,-1)	$M_\circ^{hex}(a_{11})=\frac{3\sqrt{3}}{4}$ [(2+6-1)(0.6)+(4+8-5)(0.4)] = 9.0
a_{12}=(0, 1, 2, 3, 4, 6)	$M_\circ^{hex}(a_{12})=\frac{3\sqrt{3}}{4}$ [(0+2+6)(0.6)+(1+3+4)(0.4)] = 10.3
a_{13}=(-3, -2, 2, 3, 4, 6)	$M_\circ^{hex}(a_{13})=\frac{3\sqrt{3}}{4}$ [(-3+2+6)(0.6)+(-2+3+4)(0.4)] = 6.4
a_{14}=(0, 2, 4, 6, -7, -3)	$M_\circ^{hex}(a_{14})=\frac{3\sqrt{3}}{4}$[(0+4-3)(0.6)+(2+6-7)(0.4)] = 1.2
a_{15}=(0, 1, 2, 3, 8, 10)	$M_\circ^{hex}(a_{15})=\frac{3\sqrt{3}}{4}$[(0+2+10)(0.6)+(1+3+8)(0.4)] = 15.5
a_{21}=(-8,-7,4,6,7,10)	$M_\circ^{hex}(a_{21})=\frac{3\sqrt{3}}{4}$ [(-8+4+10)(0.6)+(-7+6+7)(0.4)] = 7.7
a_{22}=(-2,-1,0,1,4,6)	$M_\circ^{hex}(a_{22})=\frac{3\sqrt{3}}{4}$ [(-2+0+6)(0.6) + (-1+1+4)(0.4)] = 5.1
a_{23} = (-6,-5,6,8,0,3)	$M_\circ^{hex}(a_{23})=\frac{3\sqrt{3}}{4}$[(-6+6+3)(0.6)+(-5+8+0)(0.4)] = 3.8
a_{24}= (-4,-3,8,10,2,5)	$M_\circ^{hex}(a_{24})=\frac{3\sqrt{3}}{4}$[(-4+8+5)(0.6)+(-3+10+2)(0.4)] = 11.6
a_{25} = (-4, -3, 1, 2, 3, 5)	$M_\circ^{hex}(a_{25})=\frac{3\sqrt{3}}{4}$[(-4+1+5)(0.6)+(-3+2+3)(0.4)] = 2.5

Step: 2 The payoff matrix is

$$\text{Player A} \overset{\text{Player B}}{\begin{pmatrix} 9 & 10.3 & 6.4 & 1.2 & 15.5 \\ 7.7 & 5.1 & 3.8 & 11.6 & 2.5 \end{pmatrix}} \quad \begin{matrix} \textbf{Row Minimum} \\ \textbf{1.2} \\ \textbf{2.5} \end{matrix}$$

Col. Maximum 9 10.3 6.4 11.6 15.5

min-max = **6.4** and max-min = **2.5**

Therefore, it has no saddle point.

Step: 3 Reduce the given matrix by using the graphical method. Let us write the payoff equations of B when he plays different strategies. A has only two strategies. Let us assume that A plays his first strategy with a probability x and his second strategy with a probability (1-x). The B's payoffs are,

P_1 for B's first strategy = 9x +7.7(1-x) = 1.3x + 7.7
When x=1 ; P_1= 9 and when x=0 ; P_1= 7.7

P_2 for B's second strategy = 10.3x +5.1(1-x) = 5.2x + 5.1
When x=1 ; P_2= 10.3 and when x=0 ; P_2= 5.1

P_3 for B's third strategy = 6.4x +3.8(1-x) = 2.6x + 3.8
When x=1 ; P_3= 6.4 and when x=0 ; P_3= 3.8

P_4 for B's fourth strategy = 1.2x +11.6(1-x) = 11.6 - 10.4x
When x=1 ; P_4= 1.2 and when x=0 ; P_4= 11.6

P_5 for B's fifth strategy = 15.5x +2.5(1-x) = 13x + 2.5
When x=1 ; P_5= 15.5 and when x=0 ; P_5= 2.5

Step: 4 Plot these payoffs on the graph,

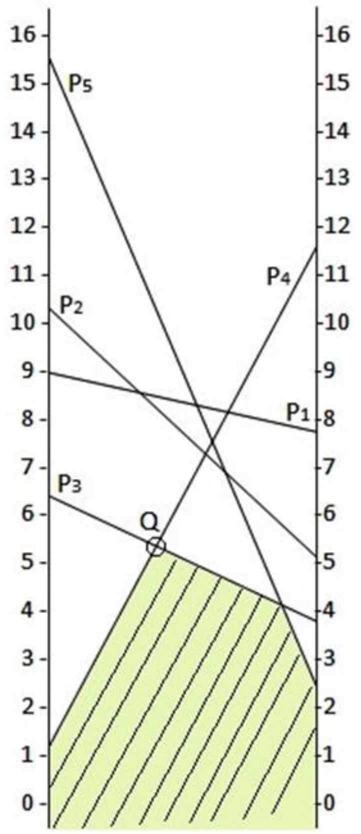

Figure No 2: Graphical Representation of the Payoff lines in Example 1.

After drawing the graph, the lower bound is marked and the highest point of the lower bound (i.e. max-min) is point Q lying on the intersection of lines P_3 and P_4. Now the game is reduced to 2×2 matrix. For this payoff we have to find the optimal strategies of A and B. The reduced game is,

$$\text{Player A} = \begin{pmatrix} 6.4 & 1.2 \\ 3.8 & 11.6 \end{pmatrix}$$

	Player B		**Row Minimum**
Player A	6.4	1.2	**1.2**
	3.8	11.6	**3.8**
Column Maximum	**6.4**	**11.6**	

min-max = **6.4** and max-min = **3.8**

Clearly it has no saddle point. Hence, we have to apply the formula to get the optimal strategies.

$$p1 = \frac{(a22 - a12)}{(a11 + a22) - (a12 + a21)} = \frac{11.6-1.2}{(6.4 + 11.6) - (1.2 + 3.8)} = \frac{10.4}{18-5} = \frac{10.4}{13}$$

$$p_2 = 1 - p_1 = 1-\frac{10.4}{13} = \frac{2.6}{13}$$

$$q1 = \frac{(a22 - a21)}{(a11 + a22) - (a12 + a21)} = \frac{11.6-3.8}{(6.4+11.6)-(1.2+3.8)} = \frac{7.8}{18-5} = \frac{7.8}{13}$$

$$q_2 = 1 - q_1 = 1- \frac{7.8}{13} = \frac{5.2}{13}$$

Value of the game (V) = $\frac{(a11a22 - a12a21)}{(a11 + a22) - (a12 + a21)} = \frac{(6.4)(11.6) - (1.2)(3.8)}{(6.4 + 11.6) - (1.2 + 3.8)} = \frac{74.24 - 4.56}{18 - 5} = \frac{69.68}{13}$

Therefore, $S_A = \left(\frac{10.4}{13}, \frac{2.6}{13}\right)$; and $S_B = \left(0, 0, \frac{7.8}{13}, \frac{5.2}{13}, 0\right)$

Example 2

Consider the following fuzzy game problem

	Player B	
Player A	(2, 4, 6, 8, -5,-1)	(0, 1, 2, 3, 4, 6)
	(-8, -7, 4, 6, 7, 10)	(-2, -1, 0, 1, 4, 6)
	(-6, -5, 6, 8, 0, 3)	(-3, -2, 2, 3, 4, 6)
	(-4, -3, 8, 10, 2, 5)	(0, 2, 4, 6, -7, -3)
	(-4, -3, 1, 2, 3, 5)	(0, 1, 2, 3, 8, 10)

Solution: The measure of $\tilde{A}$ is calculated as

$$M_{\circ}^{hex}(\tilde{A}) = \frac{3\sqrt{3}}{4}\ [\ (a_1+a_3+a_6)(k) + (a_2+a_4+a_5)(1-k)]$$

Step: 1 Change the given fuzzy problem into a crisp value problem. Here, the value of k = 0.6,

Table No 2: Shows the crisp values of the hexagonal fuzzy numbers in Example 2.

a_{11} = (2, 4, 6, 8, -5,-1)	$M_{\circ}^{hex}(a_{11})=\frac{3\sqrt{3}}{4}$ [(2+6-1)(0.6)+(4+8-5)(0.4)] = 9.0
a_{12}= (0, 1, 2, 3, 4, 6)	$M_{\circ}^{hex}(a_{12})=\frac{3\sqrt{3}}{4}$ [(0+2+6)(0.6)+(1+3+4)(0.4)] = 10.3
a_{21} = (-8, -7, 4, 6, 7, 10)	$M_{\circ}^{hex}(a_{21})=\frac{3\sqrt{3}}{4}$ [(-8+4+10)(0.6)+(-7+6+7)(0.4)] = 7.7
a_{22} = (-2, -1, 0, 1, 4, 6)	$M_{\circ}^{hex}(a_{22})=\frac{3\sqrt{3}}{4}$ [(-2+0+6)(0.6)+(-1+1+4)(0.4)] = 5.1
a_{31} = (-6, -5, 6, 8, 0, 3)	$M_{\circ}^{hex}(a_{31})=\frac{3\sqrt{3}}{4}$ [(-6+6+3)(0.6)+(-5+8+0)(0.4)] = 3.8
a_{32} = (-3, -2, 2, 3, 4, 6)	$M_{\circ}^{hex}(a_{32})=\frac{3\sqrt{3}}{4}$ [(-3+2+6)(0.6)+(-2+3+4)(0.4)] = 6.4
a_{41} = (-4, -3, 8, 10, 2, 5)	$M_{\circ}^{hex}(a_{41})=\frac{3\sqrt{3}}{4}$ [(-4+8+5)(0.6)+(-3+10+2)(0.4)] = 11.6
a_{42} = (0, 2, 4, 6, -7, -3)	$M_{\circ}^{hex}(a_{42})=\frac{3\sqrt{3}}{4}$ [(0+4-3)(0.6)+(2+6-7)(0.4)] = 1.2
a_{51} = (-4, -3, 1, 2, 3, 5)	$M_{\circ}^{hex}(a_{51})=\frac{3\sqrt{3}}{4}$ [(-4+1+5)(0.6)+(-3+2+3)(0.4)] = 2.5
a_{52} = (0,1, 2,3,8,10)	$M_{\circ}^{hex}(a_{52})=\frac{3\sqrt{3}}{4}$ [(0+2+10)(0.6)+(1+3+8)(0.4)] = 15.5

Step: 2 The payoff matrix is

	Player B		**Row Minimum**
Player A	9	10.3	**9**
	7.7	5.1	**5.1**
	3.8	6.4	**3.8**
	11.6	1.2	**1.2**
	2.5	15.5	**2.5**
Column maximum	**11.6**	**15.5**	

min-max = **11.6** and max-min = **9**

Therefore, it has no saddle point.

Step: 3 Reduce the given matrix by using the graphical method. Let us write the payoff equations of A when he plays different strategies. B has only two strategies. Let us assume that B plays his first strategy with a probability x and his second strategy with a probability (1-x). The A's payoffs are,

P_1 for A's first strategy = 9x + 10.3(1-x) = 10.3 – 1.3x
When x=1; P_1= 9 and when x=0; P_1= 10.3

P_2 for A's second strategy = 7.7x + 5.1(1-x) = 2.6x + 5.1
When x=1; P_2= 7.7 and when x=0; P_2= 5.1

P_3 for A's third strategy = 3.8x + 6.4(1-x) = 6.4 – 2.6x
When x=1; P_3= 3.8 and when x=0; P_3= 6.4

P_4 for A's fourth strategy = 11.6x + 1.2(1-x) = 10.4x + 1.2
When x=1; P_4= 11.6 and when x=0; P_4= 1.2

P_5 for A's fifth strategy = 2.5x + 15.5(1-x) = 15.5 -13x
When x=1; P_5= 2.5 and when x=0; P_5= 15.5

Step: 4 Plot the above payoffs on the graph

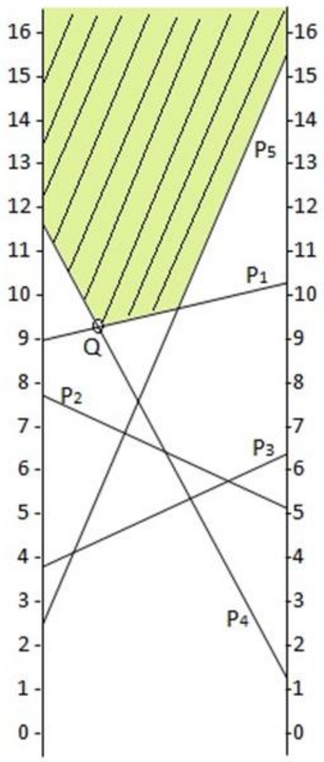

Figure No 3: Graphical Representation of the Payoff lines in Example 2.

After drawing the graph, the upper bound is marked and the lowest point of the upper bound (i.e. min-max) is point Q lying on the intersection of lines P_1 and P_4. Now the game is reduced to 2×2 matrix. For this payoff we have to find the optimal strategies of A and B. The reduced game is,

	Player B		**Row Minimum**
Player A	9	10.3	**9**
	11.6	1.2	**1.2**
Column Maximum	**11.6**	**10.3**	

min-max = **10.3** and max-min = **9**

Clearly it has no saddle point. Hence, we have to apply the formula to get the optimal strategies.

$$p_1 = \frac{(a22 - a12)}{(a11 + a22) - (a12 + a21)} = \frac{1.2 - 10.3}{(9 + 1.2) - (10.3 + 11.6)} = \frac{-9.1}{10.2 - 21.9} = \frac{9.1}{11.7}$$

$$p_2 = 1 - p_1 = 1 - \frac{9.1}{11.7} = \frac{2.6}{11.7}$$

$q_1 = \frac{(a22 - a21)}{(a11 + a22) - (a12 + a21)} = \frac{1.2 - 11.6}{(9 + 1.2) - (10.3 + 11.6)} = \frac{-10.4}{10.2 - 21.9} = \frac{10.4}{11.7}$

$q_2 = 1 - q_1 = 1 - \frac{10.4}{11.7} = \frac{1.3}{11.7}$

Value of the game (V) $= \frac{(a11a22 - a12a21)}{(a11 + a22) - (a12 + a21)} = \frac{(9)(1.2) - (10.3)(11.6)}{(9 + 1.2) - (10.3 + 11.6)} = \frac{10.8 - 119.48}{10.2 - 21.9} = \frac{108.68}{11.7}$

Therefore, $S_A = \left(\frac{9.1}{11.7}, 0, 0, \frac{2.6}{11.7}, 0\right)$; $S_B = \left(\frac{10.4}{11.7}, \frac{1.3}{11.7}\right)$

Conclusion

1. In this paper, a graphical method is used for solving the fuzzy game problem.
2. In the above two examples we have considered only (5×2) and (2×5) fuzzy game but the method applied here can be used to solve any (2×n) and (n×2) fuzzy game.
3. If the condition $a_1+a_3+a_6 = a_2+a_4+a_5$ is satisfied by the hexagonal fuzzy numbers then we will get the same game value for any value of k $(0 \le k \le 1)$.

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