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Mathematical Analysis of Fuzzy Transportation Problems

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Abstract: Transportation problems are vital in logistics and supply chain management under uncertain conditions. This study investigates fuzzy tetrahedral transportation problems (TFTP) by modeling transportation costs as tetrahedral fuzzy numbers to capture real-world uncertainties. Allocation Table Method (ATM), Russell's Approximation Method (RAM), and a Heuristic Method are compared using the robust ranking technique. Initial basic feasible solutions are evaluated, and optimality is confirmed using the MODEM algorithm. Results show that RAM consistently produces solutions closest to the optimum, while ATM and the Heuristic Method exhibit greater deviations. According to the study's findings, RAM is the best approach for accurately and economically resolving fuzzy transportation problems.

Keywords: *Fuzzy Transportation Problem; Fuzzy Number; Ranking Technique, Initial Basic Feasible Solution, Optimal Solution, Russel's Approximation, Heuristic Method.*

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I. INTRODUCTION

Fuzzy transportation problems (FTP) have gained significant attention due to their ability to handle uncertainty in real-world transportation scenarios. In practical applications such as vaccine distribution, logistics networks often face unpredictable conditions, making it essential to model transportation costs using fuzzy numbers. Traditional transportation problem-solving methods struggle with this uncertainty, necessitating the use of specialized fuzzy optimization techniques.

This project specifically deals with a Tetrahedral Fuzzy Transportation Problem (TFTP) where costs are represented as tetrahedral fuzzy numbers. The study compares three methods for solving TFTP:

- Allocation Table Method (ATM) – A structured approach to obtaining an IBFS, which often deviates from optimality.
- Russell's Approximation Method (RAM) – An efficient heuristic method that considers opportunity costs, often yielding solutions close to the optimal one.
- Heuristic Method – A problem-specific approach that provides feasible solutions without necessarily guaranteeing optimality.

To evaluate and compare these methods the Robust ranking technique is used to convert fuzzy cost into crisp values. The MODIM algorithm is employed to determine the optimal solution and the difference between IBFS and optimal cost is analyzed the objective is to demonstrate that RAM outperforms ATM and Heuristic method providing the best initial feasible solution and minimizing overall transportation cost in uncertain environment.

II. PRELIMINARIES

- *Definition*

Let X be the universe's nonempty set. A fuzzy set A in X is represented as follows: $\widetilde{A} = \{x, \ \mu_{\widetilde{A}}(x) \mid x \in X\}$ where the degree of membership of element x in the fuzzy set is represented by the function $\mu_{\widetilde{A}} : \ X \rightarrow [0, 1], \mu_{\widetilde{A}}(x)$. Thus, $\mu_{\widetilde{A}}(x)$ is valued on the unit interval.

- *Definition*

- A subset of the real line is called a fuzzy number $\widetilde{A}$
- The function of continuous membership.
- Convex, that is for any x, y ∈ R and λ ∈ [0, 1].

$$\mu_{\widetilde{A}}(\lambda x + (1 - \lambda) y) \geq \min(\mu_{\widetilde{A}}(x), \ \mu_{\widetilde{A}}(y)).$$

- Normal, that is there exist at least one x ∈ R such that $\mu_{\widetilde{A}}(x) = 1$.

- *Definition*

Let $\widetilde{A}$ and $\widetilde{B}$ be any fuzzy numbers and let ξ∈ R be any real number. Then, the sum of two fuzzy numbers and the scalar product of ξ and $\widetilde{A}$ are defined by the membership functions.

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$\mu_{\tilde{A}+\tilde{B}}(z) = \sup \min_{z=v+w} \{ \mu_{\tilde{A}}(v), \mu_{\tilde{B}}(w)\}$,

$\mu_{\xi\tilde{A}}(z) = \max \{ \sup_{z=\xi v} \mu_{\tilde{A}}(v), 0\}$, where we set up $\{\emptyset\} = -\infty$

➢ *Definition*

A Tr FN $\tilde{A}$= (l', a, b, r') a special fuzzy set in R, whose membership function is defined as follow (Figure 1):

$$\mu_{\tilde{A}}(x) = \begin{cases} (x - l')/(a - l') & \text{if } l' \le x \le a \\ 1 & \text{if } a \le x \le b \\ (r' - x)/(r' - b) & \text{if } b \le x \le r' \\ 0 & \text{otherwise} \end{cases} \quad (1)$$

where l'≤ a ≤b ≤r'.

➢ *Mathematical Formulation of Fuzzy Transportation*

The mathematical formulation of the FTP is of the following form (Table 1):

Minimize $\tilde{\psi} = \sum_{i=1}^{m} \sum_{j=1}^{n} \tilde{c}_{ij} x_{ij}$

subject to $\sum_{j=1}^{n} x_{ij} \le \alpha_i$, $i = 1, 2, ..., m$

$\sum_{i=1}^{m} x_{ij} \ge \beta_j$, j=1, 2, ..., n

$x_{ij} \ge 0$ for all i and j,

Table 1 The Fuzzy Transportation Table

	1	2	…	N	α_i
1	$\tilde{c}_{11}$	$\tilde{c}_{12}$	…	$\tilde{c}_{1n}$	α_1
2	$\tilde{c}_{21}$	$\tilde{c}_{22}$	…	$\tilde{c}_{2n}$	α_2
⋮	⋮	⋮	⋮	⋮	⋮
β_j	β_1	β_2	…	β_n	$\sum_{i=1}^{m} \alpha_i = \sum_{j=1}^{n} \beta_j$

where,

$\tilde{c}_{ij}$ is the fuzzy cost of shipping one unit of goods from its i^{th} source to j^{th} its destination.

x_{ij} is the amount that is transported from the i^{th} source to the j^{th} destination.

α_i is the goods' overall availability at the i^{th} source.

β_i is the total demand for the destination goods.

$\sum_{i=1}^{m} \sum_{j=1}^{n} \tilde{c}_{ij} x_{ij}$, is total fuzzy transportation cost.

If $\sum_{i=1}^{m} \alpha_i = \sum_{j=1}^{n} \beta_j$, then FTP is said to be balanced.

If $\sum_{i=1}^{m} \alpha_i \neq \sum_{j=1}^{n} \beta_j$, then FTP is said to be unbalanced.

III. ALGORITHM TO FIND AN INITIAL BASIC FEASIBLE SOLUTION (IBFS)

➢ *Allocation Table Method*

- Step 1: The first step is to express the fuzzy linear programming problem in a tabular format, specifically a Fuzzy Transportation Table (FTT). The transportation costs are represented as fuzzy numbers and converted into approximate crisp values using the Robust Ranking Technique.
- Step 2: Check whether the fuzzy transportation problem is balanced. If it is unbalanced, balance it by introducing a dummy source or destination.
- Step 3: Identify the minimum odd cost among all cost cells in the FTT. If no odd cost exists, divide all cost values by 2 repeatedly until at least one odd cost appears.
- Step 4: Construct the Allocation Table by retaining the minimum odd cost in its corresponding cell(s) and subtracting this minimum odd cost from all other odd-valued cost cells of the FTT. The resulting values are termed allocation cell values.
- Step 5: Begin allocation with the cell corresponding to the minimum odd cost identified in Step 3. Allocate the maximum feasible quantity (minimum of supply and demand), and delete the satisfied row or column.
- Step 6: Select the cell with the minimum allocation cell value and allocate the minimum of the remaining supply or demand.

✓ If multiple cells share the same allocation cell value, select the cell allowing the minimum allocation.
✓ If a tie persists, choose the cell with the minimum transportation cost from the original FTT.
✓ If still tied, select the cell closest to the minimum of the remaining supply or demand.
✓ Delete the fully satisfied row or column after allocation.

- Step 7: Repeat Step 6 until all supplies and demands are completely satisfied.
- Step 8: Compute the total fuzzy transportation cost using the original FTT and the obtained allocation.

➢ *Modified Distribution Method (Modim) for Finding Optimal Solution*

In this section, we find the best solution for FTP using a modified method of distribution. Algorithm of MODIM is illustrated as follows:

- Step-1: Find IBFS by proposed ATM.
- Step-2: Compute dual variables R_i and K_j for all row and column, respectively, satisfying $C_{ij} = R_i + K_j$, set $R_1 = 0$.
- Step-3: Calculate the improvement index value for unoccupied cells by the equation $E_{ij} = C_{ij} - R_i - K_j$.
- Step-4: Consider valued of E_{ij}.

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- ✓ case (i) IBFS is fuzzy optimal solution, if $E_{ij} \geq 0$ for every unoccupied cells.
- ✓ case (ii) IBFS is not fuzzy optimal solution, for at least one $E_{ij} < 0$. Go to step 5.

- Step-5: Choose the unoccupied cell for the most negative value of E_{ij}.
- Step 6: Construct a closed loop starting from the selected unoccupied cell. Move alternately in horizontal and vertical directions through occupied cells and return to the starting cell. Assign "+" and "–" signs alternately at the loop corners, beginning with a "+" sign at the selected unoccupied cell.
- Step 7: Identify the minimum allocation value among the cells marked with the "–" sign. Add this value to all cells with the "+" sign and subtract it from all cells with the "–" sign.
- Step 8: The adjustments in Step 7 yield an improved Basic Feasible Solution (BFS).
- Step 9: Test the optimality condition for improved BFS. The process is complete when $E_{ij} \geq 0$ for all the empty cell.

➢ *Russell's Approximation Method*

- Step 1: Balance TP if necessary.
- Step 2: Compute $\overline{A}_i$ for all rows and $\overline{B}_j$ for all columns, then form $\gamma_{ij} = C_{ij} - (\overline{A}_i + \overline{B}_j)$.
- Step 3: Repeatedly allocate to the cell with the most negative γij, updating affected row/column totals, until all demands and supplies are satisfied.

➢ *Heuristic Method*

- Step-1: Check the problem is balanced or not.
- Step-2: Cost difference between high cost and low cost, row/column, gives penalty cost.
- Step-3: Allocate as much as possible to this variable adjust it and continue the procedure, until get the best result.

➢ *Numerical Example*

A government health agency is distributing COVID-19 vaccines from three manufacturing plants to three hospitals in different cities. Due to uncertainties like weather, road conditions, and fuel prices, transportation costs are represented as tetrahedral fuzzy numbers instead of fixed values. The goal is to minimize transportation cost while meeting supply and demand constraints.

Table 2 The Fuzzy Transportation Table (FTT)

Source	**H₁**	**H₂**	**H₃**	**Supply (α_i)**
P_1	(16,18,19,21)	(22,23,25,26)	(28,29,31,32)	30
P_2	(13,14,15,16)	(22,23,24,25)	(19,20,22,23)	20.5
P_3	(14,15,16,17)	(20,21,23,24)	(21,22,24,25)	41
Demand(β_j)	26	15	19.5	

Solution:

IV. ALLOCATION TABLE METHOD

Table 3 FTT by ATM

Source	**H_1**	**H_2**	**H_3**	**Supply (α_i)**
P_1	(16,18,19,21)	(22,23,25,26)	(28,29,31,32)	30
P_2	(13,14,15,16)	(22,23,24,25)	(19,20,22,23)	20.5
P_3	(14,15,16,17)	(20,21,23,24)	(21,22,24,25)	41
Demand(β_j)	26	15	19.5	

We compute the TrFN's membership function using Robust's ranking method.

Table 4 FTT After Ranking

Source	**H_1**	**H_2**	**H_3**	**H_4**	**Supply**
P_1	18.5	24	30	0	30
P_2	14.5	23.5	21	0	20.5
P_3	15.5	22	23	0	41
Demand	26	15	19.5	31	

The minimum odd cost is 14.5.

This exhausts the capacity of P_2 and leaves 26 – 20.5 = 5.5 units with H_1.

Table 5 The Modified FTT After Ranking is

Source	**H_1**	**H_2**	**H_3**	**H_{dummy}**	**Supply**
P_1	18.5	24	30	0	30

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P_2	~~14.5 (20.5)~~	~~23.5~~	~~21~~	0	--
P_3	15.5	22	23	0	41
Demand	26 – 20.5 = 5.5	15	19.5	31	

The minimum cost is 15.5. And this uses up all of H1's capacity, leaving 41–5.5 = 35.5 units with P3.

By similar process we get the initial feasible solution is

Table 6 Initial Feasible Solution by ATM

Source	H_1	H_2	H_3	H_4	Supply
P_1	18.5	24	30	0(30)	30
P_2	14.5(20.5)	23.5	21	0	20.5
P_3	15.5(5.5)	22(15)	23(19.5)	0(1)	41
Demand	26	15	19.5	31	

The minimum total transportation cost is 20.5*14.5 + 30*0 + 5.5*15.5 + 15*22 + 19.5*23 + 1*0 = 11,61.

Here, the number of allocated cells = 6, which is equal to m + n - 1 = 3 + 4 - 1 = 6. This solution is non-degenerate.

We now use MODIM to find the answer.

Table 7 Initial Feasible Solution by MODIM

Source	H_1	H_2	H_3	H_4	Supply
P_1	18.5	24	30	0(30)	30
P_2	14.5(20.5)	23.5	21	0	20.5
P_3	15.5(5.5)	22(15)	23(19.5)	0(1)	41
Demand	26	15	19.5	31	

- *Iteration-1*

- Step 1: Computing bi-variate R_i and K_j for all row and column, respectively, satisfying $C_{ij} = R_i + K_j$.

- *Substituting $R_1 = 0$.*

2. $C_{14} = R_1 \Rightarrow K_4 = C_{14} - R_1 = 0 - 0 = 0$

3. $C_{21} = R_2 + K_1 \Rightarrow R_2 = C_{21} - K_1 = 14.5 - 15.5 = -1$

4. $C_{31} = R_3 + K_1 \Rightarrow K_1 = C_{31} - R_3 = 15.5 - 0 = 15.5$

5. $C_{32} = R_3 + K_2 \Rightarrow K_2 = C_{32} - R_3 = 22 - 0 = 22$

6. $C_{33} = R_3 + K_3 \Rightarrow K_3 = C_{33} - R_3 = 23 - 0 = 23$

7. $C_{34} = R_3 + K_4 \Rightarrow R_3 = C_{34} - K_4 = 0 - 0 = 0$

Table 8 I Iteration Table by MODIM

Source	H_1	H_2	H_3	H_{dummy}	Supply	R_i
P_1	18.5	24	30	0 (30)	30	$R_1 = 0$
P_2	14.5(20.5)	23.5	21	0	20.5	$R_2 = -1$
P_3	15.5(5.5)	22(15)	23(19.5)	0(1)	41	$R_3 = 0$
Demand	26	15	19.5	31		
K_j	$K_1 = 15.5$	$K_2 = 22$	$K_3 = 23$	$K_4 = 0$		

Iterating similarly we get,

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Table 9 Final Optimal Solution by MODIM

Source	H_1	H_2	H_3	Hdummy	Supply
P_1	18.5	24	30	0(30)	30
P_2	14.5(1)	23.5	21(19.5)	0	20.5
P_3	15.5(25)	22(15)	23	0(1)	41
Demand	26	15	19.5	31	

The minimum fuzzy transportation cost = 0 * 30 + 14.5 * 1 + 21 * 19.5 + 15.5 * 25 + 22 * 15+ 0 * 1 = 1141.5.

V. RUSSELL'S APPROXIMATION METHOD

From fuzzy transportation problem after ranking, we get (TABLE 4), Total Demand = 60.5 is less than Total Supply = 91.5. So, We add a dummy demand constraint with 0-unit cost and with allocation 31.

Now, the modified table is,

Table 10 The First Modified Table in RAM

Source	**H1**	**H2**	**H3**	**Hdummy**	**Supply**
P_1	18.5	24	30	0	30
P_2	14.5	23.5	21	0	20.5
P_3	15.5	22	23	0	41
Demand	26	15	19.5	31	

By similar iteration , we get

Table 11 Initial Feasible Solution in RAM

Source	**H_1**	**H_2**	**H_3**	**Hdummy**	**Supply**
P_1	18.5	24	30	0(30)	30
P_2	14.5(1)	23.5	21(19.5)	0	20.5
P_3	15.5(25)	22(15)	23	0(1)	41
Demand	26	15	19.5	31	

The minimum total transportation cost = 0 * 30 + 14.5 * 1 + 21 * 19.5 + 15.5 * 25 + 22 * 15 + 0 * 1 = 1141.5.

Now we apply MODIM method using Table (11)

➢ *Iteration-1*

- Step 1: Now Computing dual variables R_i and K_j for all row and column, respectively, satisfying $C_{ij} = R_i + K_j$.

Table 12 Iteration Table of Step 1

Source	**H_1**	**H_2**	**H_3**	**H_{dummy}**	**Supply**	**R_i**
P_1	18.5	24	30	0 (30)	30	$R_1 = 0$
P_2	14.5(1)	23.5	21(19.5)	0	20.5	$R_2 = -1$
P_3	15.5(25)	22(15)	23	0(1)	41	$R_3 = 0$
Demand	26	15	19.5	31		
K_j	$K_1 = 15.5$	$K_2 = 22$	$K_3 = 22$	$K_4 = 0$		

- Step 2: Now we Calculate the improvement index value for unoccupied cells by the equation

$E_{ij} = C_{ij} - R_i - K_j$

$E_{11} = C_{11} - (R_1 + K_1) = 18.5 – (0+15.5) = 3$ $E_{12} = C_{12} - (R_1 + K_2)$

$= 24 – (0+22) = 2$

$E_{13} = C_{13} - (R_1 + K_3) = 30 – (0+22) = 8$

$E_{22} = C_{22} - (R_2 + K_2) = 23.5 – (-1+22) = 2.5$

$E_{23} = C_{23} - (R_2 + K_3) = 0 – (-1+0) = 1$

$E_{33} = C_{33} - (R_3 + K_3) = 23 – (0+22) = 1$

- Step 3: Since all the values of $E_{ij} \geq 0$. It is the fuzzy optimal solution.

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Table 13 Final Optimal Solution by RAM

Source	H_1	H_2	H_3	Hdummy	Supply
P_1	18.5	24	30	0(30)	30
P_2	14.5(1)	23.5	21(19.5)	0	20.5
P_3	15.5(25)	22(15)	23	0(1)	41
Demand	26	15	19.5	31	

The minimum fuzzy transportation cost = 0 * 30 + 14.5 * 1 + 21 * 19.5 + 15.5 * 25 + 22 * 15+ 0 * 1 = 1141.5

VI. HEURISTIC METHOD

FTT after ranking (Table 4), we get Total Demand = 60.5 is less than Total Supply = 91.5. So, we add a dummy demand constraint with 0-unit cost and with allocation 31.

Table 14 The Modified Table by H.M

Source	H1	H2	H3	Hdummy	Supply
P_1	18.5	24	30	0	30
P_2	14.5	23.5	21	0	20.5
P_3	15.5	22	23	0	41
Demand	26	15	19.5	31	

Similarly proceeding we obtain the

Table 15 Initial Feasible Solution by HM

Source	H_1	H_2	H_3	H_{dummy}	Supply	Row Penalty
P_1	18.5	24	30	0(30)	30	|30|--|--|--|--|--|
P_2	14.5(19.5)	23.5	21	0(1)	20.5	|23.5 |23.5|9|--|--|--|
P_3	15.5(6.5)	22(15)	23(19.5)	0	41	|23|23|7.5|7.5|1|0|
Demand	26	15	19.5	31		
Column Penalty	4 1 1 0 -- --	2 1.5 1.5 0 0 --	9 2 2 0 0 0	0 0 -- -- -- --		

The minimum total transportation cost = 0*30 + 14.5*19.5 + 0*1 + 15.5*6.5 + 22*15 + 23*19.5 = 1162.

Here, the number of allocated cells = 6 is equal to m + n - 1 = 3 + 4 - 1 = 6. This solution is non-degenerate.

Now we apply MODIM, to compute the optimal solution of table (6)

- *Iteration-1*

- Step 1: Now Computing bi-variate R_i and K_j for all row and column, respectively, satisfying $C_{ij} = R_i + K_j$.

Table 16 Iteration-1 by HM

Source	H_1	H_2	H_3	H_{dummy}	Supply	R_i
P_1	18.5	24	30	0(30)	30	$R_1 = 0$
P_2	14.5(19.5)	23.5	21	0(1)	20.5	$R_2 = 0$
P_3	15.5(6.5)	22(15)	23(19.5)	0	41	$R_3 = 1$
Demand	26	15	19.5	31		
K_j	$K_1 = 14.5$	$K_2 = 21$	$K_3 = 22$	$K_4 = 0$		

- Step 2: Now we Calculate the improvement index value for unoccupied cells by the equation $E_{ij} = C_{ij} - R_i - K_j$

Now choose the most minimum negative value from all E_{ij} = E_{23} = [-1] and draw a closed path from P_2H_3

Closed path is P_2H_3 ⟶ P_2H_3 ⟶ P_2H ⟶ P_2H_3

Minimum allocated value among all negative position (-) on closed path = 19.5 Subtract 19.5 from all (-) and add it to all (+)

Table 17 Final Table of Iteration I in HM

Source	H_1	H_2	H_3	H_{dummy}	Supply
P_1	18.5	24	30	0(30)	30
P_2	14.5	23.5	21(19.5)	0(1)	20.5
P_3	15.5(26)	22(15)	23	0	41
Demand	26	15	19.5	31	

Here, the number of allocated cells = 5, which is one less than to m + n - 1 = 3 + 4 - 1 = 6. This solution is degenerate.

The quantity d is assigned to P_2H_1 , which has the minimum transportation cost = 14.5.

Proceeding in the same way we obtain

Table 18 Optimal solution by H.M

Source	H_1	H_2	H_3	Hdummy	Supply
P_1	18.5	24	30	0(30)	30
P_2	14.5(1)	23.5	21(19.5)	0	20.5
P_3	15.5(25)	22(15)	23	0(1)	41
Demand	26	15	19.5	31	

The minimum fuzzy transportation cost = 0 * 30 + 14.5 * 1 + 21 * 19.5 + 15.5 * 25 + 22 * 15+ 0 * 1 = 1141.5

Table 19 Comparing ATM and Ram and Hm Methods:

S.No	METHODS	IBFS	OPTIMAL SOLUTION
1.	ALLOCATION TABLE METHOD	1161	1141.5
2.	RUSSEL'S APPROXIMATION METHOD	1141.5	1141.5
3.	HEURISTIC METHOD	1162	1141.5

VII. CONCLUSION

This study compares ATM, RAM, and a Heuristic Method for solving Tetrahedral Fuzzy Transportation Problems and demonstrates the clear superiority of Russell's Approximation Method (RAM). The results show that RAM consistently yields an initial basic feasible solution closest to the optimal solution, while ATM and the Heuristic Method exhibit greater deviations. These findings establish RAM as a more efficient and reliable approach for fuzzy transportation problems involving cost uncertainty. The study contributes to fuzzy optimization research and supports the application of RAM in practical domains such as healthcare logistics, supply chain management, and industrial transportation planning.

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