Genetic Algorithm Based Fuzzy Multi-objective Nonlinear Programming of Regional Water Allocation

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Abstract—A genetic algorithm (GA) based approach to solve a fuzzy multi-objective nonlinear programming (FMNP) problem is presented and applied to water resources allocation. A FMNP model of regional water allocation is established originally. The objective functions of the model include three conflicting goals which are economic profits, environment goal and society goal. By turning the FMNP to an optimal level cut problem, the “fuzzy optimal solution” is solved by using a genetic algorithm. An example of the Dongying’s water allocation strategy is provided by using the proposed method.

Keywords—fuzzy multi-objective programming, fuzzy optimal solution, water resource optimal allocation, genetic algorithm

I. INTRODUCTION

Water shortage is a serious problem in the north China which affects the people’s life and economic development directly. Thus water management is one of the most important problems for Chinese government. To satisfy the growing of the demand, a scientific programming is required to allocate the limited water resource to meet the demand for some regions.

Many researchers have applied mathematical programming to water management. The traditional optimization methods attempted to obtain the optimal value to satisfy the objective function and constrains[2,5,6,11]. Grounder water quality management is investigated in [3,7]. Water supply capacity expansion problem is studied in [1]. Water distribution optimization problem is discussed in [4,5]. Generally, the mentioned works are deterministic linear or nonlinear programming problems. Recently, some researchers are studying the water management by using fuzzy programming[8, 12].

In this paper, considering some uncertainty and the different benefits of water allocation among industry, agriculture, residential consumption and environment in a region, a FMNP model is established. A GA based solving approach for FMNP is presented. By using the optimal level cut idea, the FMNP is changed to be a single objective nonlinear programming problem which is easily solved with GA. To show the validity of the method, a FMNP model of Dongying city’s water allocation is built and the “fuzzy optimal solutions” are provided.

II. A FMNP MODEL OF REGIONAL WATER RESOURCE ALLOCATION

A FMNP model of regional water resource allocation is established as follows.

A. Objective functions

(i) Economic profit function

\[ \max \tilde{f}_j(x) \]

\[ = \sum_k \sum_i [\sum_i (b^i_j - a^i_j)x^i_k - \alpha_k] + \sum(a^i_k - a^i_j)x^i_k - \alpha_k] \]

where

\( \tilde{f}(x) \) - a function which can be fuzzified, means that the value of objective function can vary in some domain. The domain is called the admissible error variable region.

\( f_i(x) \) - net profit of all regions water allocated.

\( X \) - the decision variables.

\( k \) - the kth sub-area.

\( i \) - the ith independent water resource of some subarea.

\( p \) - the pth common water resource.

\( x^i_k \) - the amount of water released from i source of kth sub-area to jth plant, the outflow of water.

\( b^i_j \) - the profit of per unit released water from i source of kth sub-area to jth plant.

\( a^i_k \) - the cost of per unit released water from i source of kth sub-area to jth plant.

(ii) Environmental objective function

The environmental objective is determined by the water quality and can be formulated by the amount of released
pollution water. Generally, the objective function is to minimize the amount of some important matters such as Biochemical Oxygen Demand (BOD) and Chemical Oxygen Demand (COD).

\[ \text{Min } \bar{f}_2(x) = \sum_k \sum_j \left( \sum_i P_{ij}^x + \sum_p P_{jp}^x \right) \]  

where

\[ f_i(x) \text{- the amount of pollution matter (BOD and COD) of the region.} \]

\[ P_{ij}^x \text{- the pollution matter of per unit released water from } i \text{ source of } k \text{th sub-area to } j \text{th plant.} \]

(iii) Social objective function

The social objective function is formulated by minimizing water shortage of the residents and plants.

\[ \text{Min } \bar{f}_3(x) = \sum_k \left[ D_j^x - \left( \sum_i x_{ij}^x + \sum_p x_{jp}^x \right) \right] \]  

where

\[ f_i(x) \text{- water shortage of the residential life and plants.} \]

\[ D_j^x \text{- the planning required water of } j \text{th plant of } k \text{th sub-area.} \]

B. Constraints condition

(i) Capacity constraints of water resources

Constraints of independent water resources

\[ \sum_k x_{ij}^x \leq W_i \]  

Constraints of common water resources

\[ \sum_k \sum_p x_{jp}^x \leq W_p \]  

where \( W_i \) is the upper limit of the amount of \( i \)th water resource.

(ii) Constraints of water transportations

\[ L_j^x \leq \sum_i x_{ij}^x + \sum_p x_{jp}^x \leq H_j^x \]  

(iii) Constraints of regional harmonious development.

\[ \sqrt{\mu_1 \mu_2} \geq 0.8, \]  

where \( \sqrt{\mu_1 \mu_2} \) is the coefficient of harmonious development, and \( \mu_1, \mu_2 \) is defined as follows,

\[ \mu_1(\sigma_i) = \exp(-\omega_1(\sigma_i - \sigma_i^*)^2) \]  

\[ \mu_2(\sigma_i) = \exp(-\omega_2(\sigma_i - \sigma_i^*)^2) \]  

IN (8) and (9), \( \sigma_i, \sigma_i^* \) are defined as follows,

\[ \sigma_i = \frac{1}{k} \sum_k E_i^x \]

\[ E_i^x = \left\{ \begin{array}{ll}
D_j^x - \left( \sum_j x_{ij}^x + \sum_p x_{jp}^x \right) & D_j^x \geq \sum_j \left( \sum_i x_{ij}^x + \sum_p x_{jp}^x \right) \\
1 & D_j^x < \sum_j \left( \sum_i x_{ij}^x + \sum_p x_{jp}^x \right) \end{array} \right. \]  

where

\[ D_j^x \text{- the planning required water of } j \text{th plant of } k \text{th sub-area.} \]

\[ P_i \text{- the amount of BOD and COD yielded in the reference year.} \]

\[ P \text{- the amount of BOD and COD yielded in the planning year.} \]

\[ GA_o \text{- the gross regional product per capita in the reference year.} \]

\[ GA \text{- the gross regional product per capita in the planning year.} \]

\[ \omega_1, \omega_2 \text{- the weights.} \]

From (10), we hope that the amount of consumed water of \( j \)th plant can meet the planned level. Equation (11) means that the relative increment of polluted matters is less than that of the gross regional product per capita.

(iv) Non-negative constraints

All decision variables should be non-negative.

\[ x_{ij}^x \geq 0 \]  

III. Fuzzy Nonlinear Programming (FNP) Solving via a Genetic Algorithm

Generally, a FNP problem can be described in the following form,

\[ \max f(x) = f(x_1, x_2, \cdots, x_n) \]

s.t. \[ g(x) \leq b, \]

\[ x \geq 0 \]  

where \( x = (x_1, x_2, \cdots, x_n)^T \) is \( n \) - dimensional decision variable vector, \( g(x) \) is a vector of constraint conditions, i.e.

\[ g(x) = (g_1(x), g_2(x), \cdots, g_m(x))^T \]
$b$ is a constant vector, $b = (b_1, b_2, \cdots, b_n)'$.

The FNP (13) can be turned to be the following deterministic nonlinear programming model,

$$
\begin{align*}
\text{Max } \alpha \\
\text{ s.t. } & \mu_0(x) \geq \alpha, \\
& \mu_i(x) \geq \alpha, \quad i = 1, 2, \cdots, m \\
& x \geq 0, \quad 0 \leq \alpha \leq 1,
\end{align*}
$$

(14)

Where $\alpha$ is the optimal level cut (or degree) defined as follows,

$$
\alpha = \min \{\mu_0(x), \mu_i(x), i = 1, 2, \cdots, m\}.
$$

Before solving (13) and (14), we need explain the following notations.

**Definition 1.** A fuzzy optimum of problem (13) is defined as a following fuzzy set $\tilde{S}$,

$$\tilde{S} = \{x \in (\mathbb{R}^n)' | \mu_j(x) \geq \alpha\}, \quad \alpha \in [0, 1].$$

Then, $S_\alpha$, which is called the $\alpha$ level cut of $\tilde{S}$, is an ordinary set.

**Definition 2.** $\alpha^*$ is called the optimal level cut, if $\alpha^*$ satisfies $\forall 0 \leq \alpha \leq \alpha^*, S_\alpha$ is nonempty, and $\forall \alpha > \alpha^*, S_\alpha$ is empty.

For the level cut, with the augmentation of $\alpha$, the domain of $S_\alpha$ will be reduced till there exists an $\alpha^*$ such that $\forall \delta > 0, \alpha = \alpha^* + \delta, S_{\alpha_0}$ is an empty set. $\alpha^*$ is the optimal level cut.

The idea of solving FNP via a genetic algorithm is to find a small neighborhood of $\alpha^*$, such that for all $x$ corresponding to the $\alpha$ in neighborhood of $\alpha^*$ the required optimal decision variable, i.e. fuzzy optimal solution. Thus the GA based approach can be expressed as follows. One can first set an optimal level cut $\alpha_0$, and randomly produce a population including $np$ individuals. By defining a fitness function, the individual with degree of membership no less than $\alpha_0$ is selected. The selected individuals consist of a sub-population. For reducing computing time, the individuals with degree of membership no less than $\alpha_0$ will be eliminated. The rest is a 4th sub-population in which each individual is with degree of membership $\alpha_k$ no less than $\alpha_0$. Thus $S_{\alpha_k} \subseteq S_{\alpha_0}$, every element in $S_{\alpha_k}$ is the desired optimal solution.

For individual $x$, let

$$\mu_{\min}(x) = \min\{\mu_0(x), \mu_i(x), \cdots, \mu_n(x)\}.$$

The fitness function is defined as follows.

$$F(x) = \mu_{\tilde{S}}(x) = \begin{cases} \mu_{\min}(x), & \mu_{\min}(x) \geq \alpha_0 \\ \leq \mu_{\min}(x), & \mu_{\min}(x) < \alpha_0 \end{cases}$$

(15)

where $\alpha_0$ is a pre-assigned degree of membership, and $\epsilon \in [0, 1]$.

From (15), if $x_j \notin S_{\alpha_0}$, a much small degree of membership will be set to it.

The GA based method is outlined as follows.

Step 1. Initialize the population in the search space.

Substep 1.1. Input the pre-assigned degree of membership $\alpha_0$, and the maximal iterative steps $NG$, and the number of individuals $NP$.

Substep 1.2. Input the index set $CS = \{0, 1, 2, \cdots\}$ which represent the index of the objective function and constraints respectively. For each index $x \in CS$, input the minimum and maximum of corresponding objective function or constraint.

Step 2. Produce a population and determine a membership function randomly.

Step 3. Set $k = 1$.

Step 4. For individual $j (j = 1, 2, \cdots, NP)$, calculate the fitness function $F(j)$ and selection probability $P(j)$,

$$F(j) = \mu_{\tilde{S}}(x_j), \quad P(j) = \frac{F(j)}{\sum_{i=1}^{NP} F(j)}.$$

Step 5. Perform crossover according to the crossover probability, new individuals $x_j (j = 1, 2, \cdots, NP)$ will be obtained after mutation.

Step 6. For each new individual, calculate the value of the membership function $\mu_{\tilde{S}}(x_j)$, update the optimal level cut $\mu_{\max}$, and adjust the minimum and maximum of objective function or constraints.

Step 7. $k + 1 \rightarrow k$, if $k \leq NG$, then go to Step 4 or go to Step 8.

Step 8. Output the optimal level cut $\mu_{\max}$ and the minimum and maximum of objective function or constraints.

If some constraints are inequality, penalty function can be applied to these inequalities.

IV. MODEL SOLVING OF FMNP OF WATER RESOURCE ALLOCATION

A. Fuzzification of the model

For (1)-(3), the following membership functions are defined.
For economic profit, the membership function is defined as
\[
\mu_1(x) = \begin{cases} 
1, & f_1(x) \geq z_{1g} \\
\frac{f_1(x) - l_1}{z_{1g} - l_1}, & l_1 \leq f_1(x) \leq z_{1g} \\
0, & f_1(x) \leq z_{1g}
\end{cases}
\]

For environment objective, the membership function is defined as
\[
\mu_2(x) = \begin{cases} 
1, & f_2(x) \leq z_{2g} \\
\frac{h_2 - f_2(x)}{h_2 - z_{2g}}, & z_{2g} \leq f_2(x) \leq h_2 \\
0, & f_2(x) \geq z_{2g}
\end{cases}
\]

For social objective, the membership function is defined as
\[
\mu_3(x) = \begin{cases} 
1, & f_3(x) \leq z_{3g} \\
\frac{h_3 - f_3(x)}{h_3 - z_{3g}}, & z_{3g} \leq f_3(x) \leq h_3 \\
0, & f_3(x) \geq z_{3g}
\end{cases}
\]

where
- \( z_{1g} \) - the optimal value of economic profit,
- \( l_1 \) - the lower limit of economic profit,
- \( z_{2g} \) - the optimum value of COD,
- \( z_{3g} \) - the optimum value of water shortage,
- \( h_2 \) - the upper limit of COD,
- \( h_1 \) - the upper limit of water shortage.

Then, according to above section, the fuzzy programming (1)-(12) can be turned to be a following deterministic programming model,
\[
\max \alpha \\
\text{s.t.} \\
\mu_1(x) \geq \alpha \\
\mu_2(x) \geq \alpha \\
\mu_3(x) \geq \alpha \\
G(x) \leq b \\
x \geq 0, \quad 0 \leq \alpha \leq 1.
\]

where \( \alpha \) is the optimal level cut, and \( G(x) \) denotes the constraints of (4)-(12).

B. Computation of \( z_{ig}, i = 1, 2, 3 \) and \( h_2, h_1 \).

The upper limit or lower limit of each goal can be obtained by solving the following single goal programming.

\[
\max f_1(x) = \sum_k \sum_j \left[ \sum_i (b^k_i - a^k_i)x^j_i\alpha^k_i + \sum_p (b^k_p - a^k_p)x^j_p\alpha^k_p \right]
\]

or
\[
\min f_2(x) = \sum_k \sum_j (\sum_i P^k_i x^j_i + \sum_p P^k_p x^j_p) \leq h_2
\]

or
\[
\min f_3(x) = \sum_k (D^k_j - (\sum_i x^j_i + \sum_p x^j_p)) \leq h_3
\]

s.t.
\[
\sum_k x^j_k \leq W_j, \\
\sum_k x^j_p \leq W_p, \\
L^k_j \leq \sum_i x^j_i + \sum_p x^j_p \leq H^k_j, \\
\sqrt{\mu_1 z^3} \geq 0.8, \\
x^j_k \geq 0.
\]

C. Applications to the city of Dongying

The Dongying city locates in the delta of the yellow river which is a water-short city. According to the practical situation, the supplying water area can be divided into 6 sub-areas which are the Dongying district, the Hekou district, the Guangrao county, the Lijin County, the Kenli county and the Shengli oilfield. In the Dongying district, the Hekou district, the Guangrao county, the Lijin County and the Kenli county, the water consumption includes industrial water, agricultural water, residential life water of the towns, residential life water of the countryside and environmental water. Only industrial water is considered in the Shengli oilfield. In the Dongying city, there are three water resources which are the yellow river, the rainfall and the groundwater. The yellow river and the rainfall are common water resources and the groundwater is an independent resource only in the Guangrao county.

For the water allocation of the Dongying city, we set the lower limit of the economic profit to be \( h_1 = 1.32 \times 10^8 \) yuan, the upper limit of the environmental goal to be \( h_2 = 3.6 \times 10^4 \) ton, the lower limit of social goal to be the 10% of the residential consumption water. The other parameters in the model are displayed in the following table.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( L^k_j )</td>
<td>( H^k_j )</td>
</tr>
<tr>
<td>( D^k_j )</td>
<td>( D^k_j )</td>
</tr>
<tr>
<td>( z_{1g} )</td>
<td>( z_{1g} )</td>
</tr>
<tr>
<td>( z_{2g} )</td>
<td>( z_{2g} )</td>
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<tr>
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<td>( h_2 )</td>
</tr>
<tr>
<td>( h_1 )</td>
<td>( h_1 )</td>
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</table>

V. CONCLUSIONS

This paper establishes a multi-objective fuzzy nonlinear programming problem of regional water allocation. By some manipulation, the multi-objective fuzzy nonlinear programming is turned to be an optimal level cut problem which is a single goal nonlinear programming problem and can be solved by using a genetic algorithm. Applying this method to the Dongying’s water allocation, a satisfaction solution among multi-objectives is obtained. The optimization result
could be applied to aid in the police making of the city’s water allocation.

<table>
<thead>
<tr>
<th>Sub-area</th>
<th>Paramters</th>
<th>Industrial water</th>
<th>Agricultural water</th>
<th>Life water of the towns</th>
<th>Life water of the countryside</th>
<th>Environmental water</th>
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<tbody>
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<td>425</td>
<td>23.8</td>
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<td>——</td>
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<tr>
<td></td>
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<td>3.35</td>
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<tr>
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<td>——</td>
<td>780</td>
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</tr>
</tbody>
</table>

P1- the profit per ton water (yuan/m³), P2- The cost per ton water (yuan/m³), P3- The resulted amount of COD per ton water (kg/m³), P4- $H_j$ in (6) (ten thousand m³), P5- $L_j$ in (6)(ten thousand m³), P6- Environmental water (ten thousand m³)(ten thousand m³).

<table>
<thead>
<tr>
<th>Capacity constraints</th>
<th>90% of the maximal storage (ten thousand m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Groundwater</td>
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<tr>
<td>Rainfall</td>
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### TABLE III.  THE OPTIMUM VALUE OF THE OBJECTIVES

<table>
<thead>
<tr>
<th>The objective</th>
<th>Economic profit (Ten thousand yuan)</th>
<th>Environment goal (Ten thousand ton)</th>
<th>Social goal (Ten thousand m$^3$)</th>
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</thead>
<tbody>
<tr>
<td>The value of the objective</td>
<td>14934000</td>
<td>3.391</td>
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### TABLE IV.  THE OPTIMUM DECISION VARIABLES

<table>
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<tr>
<th>Sub-area</th>
<th>Water resources</th>
<th>Industrial water</th>
<th>Agricultural water</th>
<th>residential life water of town</th>
<th>residential life water of countryside</th>
<th>Environmental water</th>
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</thead>
<tbody>
<tr>
<td>Dongying district</td>
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<td>823</td>
<td>862</td>
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<td>3150</td>
<td>219</td>
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<td>Hekou district</td>
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<td>613</td>
<td>201</td>
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<td>969</td>
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### REFERENCES


