Fuzzy Optimal Models for Gas Reservoir Management: Case of Sarajeh Gas Field (SGF)

Nooshin Jabbari and Mohd Hamdi
University of Malaya, Malaysia

Amir Naser Akhavan
AmirKabir University of Technology, Iran

Abstract

Recently the underground gas reservoirs storage becomes more important in Iran due to increase demand in cold seasons also the most oil fields in Iran developing process in gas injection strategy. So effective and successful reservoir management in underground gas fields is highly demanded. In this paper two most popular problems which are faced during operation Sarajeh Underground Gas Reservoir were discussed and the fuzzy models were designed to solve them. The first problem is the optimal model for operating Sarajeh field that fuzzy model and Fuzzy AHP (analytic hierarchy process) were applied to solve and the software was designed based on the fuzzy model. The second one is control problem which, the approach proposed by MADAN (MADAN M, 1986) was adopted and the fuzzy set rules were design. These two fuzzy model tested by historical data in field and the results show that models could be worked well.

Keywords
Reservoir management, underground gas reservoir, fuzzy set, decision making, control process

Introduction

The idea of storing natural gas in underground reservoir during low consumption seasons and use in high demand seasons and EOR projects are widely increased, especially in Iran. In this regard, gas reservoir management is a need for managing filed more effectively and optimizes gas filed performance. Therefore, optimization decision making techniques for gas reservoir operation due to multi-objectives and different disciplines involved should be applied. Applying optimization techniques for reservoir operation is not a new idea. Various techniques have been applied in an attempt to improve the efficiency of reservoir(s) operation. These techniques include Linear Programming (LP); Nonlinear Programming (NLP); Dynamic Programming (DP); Stochastic Dynamic Programming (SDP); and Heuristic Programming such as Genetic algorithms, Fuzzy logic, and Neural Networks etc.(Sinayuc, 2000& Siemek, 2006 & Ettehadtavakoli, 2006).

During the last two decades, heuristic algorithms have been developed for solving reservoir optimization problems. These algorithms use a set of points simultaneously in searching for the global optimum. (Maschio, 2008 & Patel, 2011& Tavakolian, 2004). In order to solve multi-objectives and constraints, fuzzy set theory has been successfully used and has become more and more formalized: identification, optimality issues, clustering, stability proofs and other mathematical procedures have conferred a strong mathematical background to the fuzzy approach, allowing the decision maker to decide optimal decision for operating the reservoirs (Abedini, 2011 & Shokir, 2009 & WC, 1997). According to idea of gas storage reservoir and characteristic feature of its monthly fluctuation exploitation due to variable demand depending on weather, the optimization strategy may be performed separately for some successive time periods. Each of them may show their specific optimal strategy different than other time steps. Many research and papers have been worked on fix priority objectives during the operation of gas reservoir (SINAYUC, 2000 & Siemek, 2006), but in practice real situation, the objectives weight to be changed. This idea may be realized by replacing objectives priorities in time steps. Therefore the model should be designed based on priority of objectives in current time and constrains corresponding to decision in previous step. It means that, the strategies in current period and forecasting their effects on next period by observing objectives and constrains should be formulated. In this paper, the model for field operation was developed, due to multi-objectives and multi-constraint during the operation of field in successive time periods. Model uses reservoir operation strategy in each

period by considering the effect of this strategy to next period in order to achieve optimize operation strategies for life cycle of withdrawal the field.

1- Characteristic of SGF

Sarajeh field is located some 40 km south east of city "Qum". The Qum formation (E member) constitutes the main reservoir. The E member made of argillaceous to marly limestone. The main cap rock is formed by the Upper Evaporate series. The Sarajeh structure is showing up a surface as a brachy-anticline which developed in the deposits of the Oligo-Miocene (Qum Carbonate formation) and the overlying Upper Red formation of Miocene age. Recovery factor is 69%. The gas–water contact elevation is -1819 m. The gas production from the SGF started in November 1999.

2- Optimal operation model

I composed the n time steps for operating the gas field; one considers the operation model as a state variable and operation alternatives as a decision variable. Then using the recursive method of fuzzy optimal dynamic programming.

Total number of objectives = m
Total alternatives for operating the field= a
Decision vector= D
Operation model=O
All constrains conditions= C
Objective weight vector=w

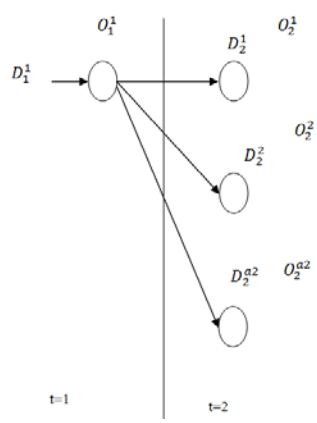


Figure 1: First phase of method

Assumed the operation alternatives for step 1, is a_1, (step 1 (t=1) D^1_1) , so each operation alternatives should be evaluate for the effect of them to next step as the bellow:

- ✓ The constrain conditions for step 2 corresponding the O^1_1 is C_2,
- ✓ The total number of satisfactory alternatives that meet the constrains is $a_2 \leq a$,

For O^1_1, D^h_2 ,(h(1,2,…,a_2) alternatives), k(1,2,…,m) objectives .

k= 1, $f_1 (D^1_2, O^1_1)$
k= 2, $f_2 (D^1_2, O^1_1,)$
⋮
k= m, $f_m (D^1_2, O^1_1)$

$$f_{m1}(D^1_2, O^1_1) = \begin{pmatrix} f_{11}(D_2^1, O_1^1) \\ \vdots \\ f_{m1}(D_2^1, O_1^1) \end{pmatrix}$$

k= 1, $f_1 (D^{a2}_2, O^1_1)$
k= 2, $f_2 (D^{a2}_2, O^1_1)$
⋮
k= m, $f_m (D^{a2}_2, O^1_1)$

$$f_{ma1} (D^{a2}, O^1_1) = \begin{pmatrix} f_{1a2}(D_2^{a2}, O_1^1) \\ \vdots \\ f_{ma2}(D_2^{a2}, O_1^1) \end{pmatrix}$$

Then, the multi- objective matrix at step 2 is:

$$F\,(D_2, O_1^1) = \begin{pmatrix} f_{11}(D_2, O_1^1) & \dots & f_{1,a_2}(D_2, O_1^1) \\ \vdots & \dots & \vdots \\ f_{m1}(D_2, O_1^1) & \dots & f_{m,a2}(D_2, O_1^1) \end{pmatrix} \qquad \text{(Equation 1)}$$

The weight vector for step 2 as following matrix due to reservoir condition:

$W_2 = w_{21} \quad \dots \quad w_{2m}$ (Equation 2)

The optimal alternative for equation 1 regarding equation 2 can be obtained by Fuzzy AHP, which methodology introduced in Appendix. If the x_{1j}^* is jth satisfactory decision for t_2 with O_1^1 finding by Fuzzy AHP. Then this process continue with O_1^2 , where the alternatives that driven form O_1^2 are a_3 , so the decision matrix for O_1^2 is

$$\begin{pmatrix} f_{11}(D_2, O_1^2) & \dots & f_{1,a_3}(D_2, O_1^2) \\ \vdots & \dots & \vdots \\ f_{m1}(D_2, O_1^2) & \dots & f_{m,a3}(D_2, O_1^2) \end{pmatrix} \qquad \text{(Equation 3)}$$

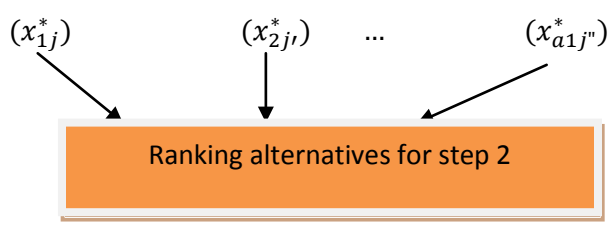
x_{2j}^* is jth satisfactory decision for t_2 with O_1^2 finding by Fuzzy AHP. Then this process continues with rest of the alternatives.

$x_{1j}^* = (D_2, O_1^1)$

$x_{2j'}^* = (D_2, O_1^2)$

$\vdots$

$x_{a1j''}^* = (D_2, O_1^{a1})$



Suppose that the x_{2i} is the best solution decision for step 2. In step 3 we start the process with O_{3i}, if this operation model cannot see the constraints in step 3, we should back and continue the process with second ranking alternative.

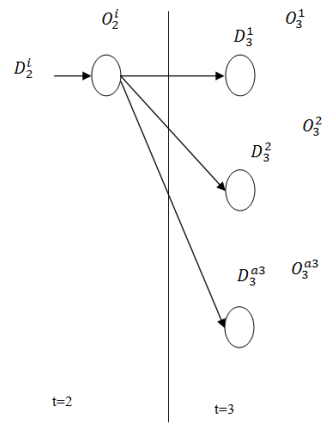


Figure 2: Second phase of method

This model is the base for mathematical software that made by authors, in which the inputs are number of alternatives, objectives and constraints in each steps and the outputs are the optimal solutions for operating the field.

Case study

The model was applied for data in SGF in 1999 when of wrong decisions made the industries in trouble. The pressure at the start of production was 19.173 MPa, minimal pressure at the end of production in first month was 11.012 because of 19 wells active in this step. So the pressure wasn't acceptable for production rate in next month and the less production made the industries in troubles. So we tested the model and found the optimal solution for each time.

t = 1 (Jan)
t =2 (Feb)
t =3 (Mar)

The objectives of reservoir management are:

I. Minimize number of wells acting in reservoir in time t(w_t)
II. Maximize rate of production in time t (q_t)

Under constraints: $q_{req} \leq q_t$ $P_{req} \leq P_t$

Table 1: minimal parameters acceptance of p,q for SGF

month	No. wells	q_t	P_t
Jan	7	20.94 (sc m^3x10^9)	14.8 MPa
Feb	15	28.36 (sc m^3x10^9)	12.5 MPa
Mar	15	21.7 (sc m^3x10^9)	10.7 MPa

In Table 1, the minimum acceptance of pressure and demand are presented. To run software first all alternatives for Jan, were simulated then for each steps due to objectives weigh, constraint, some of these alternatives omitted. The process continued until optimal model of production for each steps (by considering the effect of the strategy on next step) obtain. In the table 2 the satisfactory solution can be found through this model for each period of time to meet objectives and constraints.

Table 2: condition of parameters for each month

month	P_{req}	q_{req}	Objective weigh
Jan	14.2 MPa	20.90 (sc m^3x10^9)	(0.6,0.4)
Feb	12.3 MPa	28.3 (sc m^3x10^9)	(0.7,0.3)
Mar	10.5 MPa	21.5 (sc m^3x10^9)	(0.5,0.5)

3- Fuzzy Controller Algorithm

Recently, due to development of industries, the demand for controlling the systems with more accurate and trustable has increased and in this regard the fuzzy logic controller has played the perfect role. Fuzzy logic controller has been widely acceptable as an effective nonlinear methodology to solve the various control problems (Ramaswamy, P, 1993 & Litrico, X 1999, Rangaswamy, T,R, 2006). The first realization of the fuzzy controller using Zadeh fuzzy logic by Mamdani in 1974 (Mamdani EH, 1974) has emerged the most important application of fuzzy theory. The fuzzy control theory has been applied for many systems with varies inputs and outputs. For example for single input/ single output (SISO) structure (Hu et al, 1999). For multiple-input/ multiple output systems with strong loop interactions, the fuzzy controller work well (Lian, R 2001). Also for multistage process the conventional controller isn't effective and the advance controller conceptions are required. (Perunicic, M, 2008). A fuzzy controller is designed based on the knowledge of the process operator. This knowledge is represented as a collection of If- Then rules that relate imprecise relationships through linguistic variables (detail discussions can be found in Zadeh 1965, 1988). The essence of fuzzy logic control is to contract a set of rules based upon a combination of human reasoning, knowledge of the plant characteristics and the characteristics of the controller, from which it uses to draw conclusions. Therefore in a fuzzy logic controller the emphasis is on the human expert's behavior A fuzzy logic controller uses a set of control rules and an inference mechanism to determine the control action for a given process state. The control rules are fuzzy expressions that relate the fuzzy process variables (controller inputs) to the fuzzy controller outputs. The inference mechanism evaluates the rule base to find the appropriate control action. A typical example of such rule is: IF error is Negative and rate of change error is Negative THEN control action is Negative

In the case of SGF, the approach proposed by MADAN (MADAN M, 1986) is adopted. First the team of reservoir management defined the range of variables that use as the inputs data due to historical data and the experiments of this field (SOFREGAZ 2004), and designed the formula for each range then some rules were established, finally the model tested by some input data. In this model the error and change in error are inputs for system and the control action in output of it.

Design the model for GSF: The system that is described by fuzzy relations, in this paper is called open-loop fuzzy system with 2 inputs and 1 output (fuzzy system illustrated in Fig. 2.)

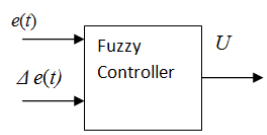


Figure 3: Fuzzy control system for SGF

The definition of a control strategy for gas outflow in SGF can be formulated as a tracking problem. The idea of controlling the system is emerged as outflow demand $q_{demand}(t)$ is defined, and a control action for seeking such that the actual gas outflow q_{out} after a transient follows the demand profile. In this regard we defined the e, Δ e

Where: $e(t) = q_{demand}(t) - q_{out}(t)$ (Equation 4)

$\Delta e(t) = e(t+1) - e(t)$ (Equation 5)

U= control action

A: Design the range for $q_{demand,\ q\ out}$

As mentioned before for this system the specific ranges for error, change error and linguistic fuzzy parameters are formulated (Akhavan, 2009) in SGF and the results are proposed in bellow diagrams for linguistic fuzzy variables by considering the SGF condition for control of outflow rate.

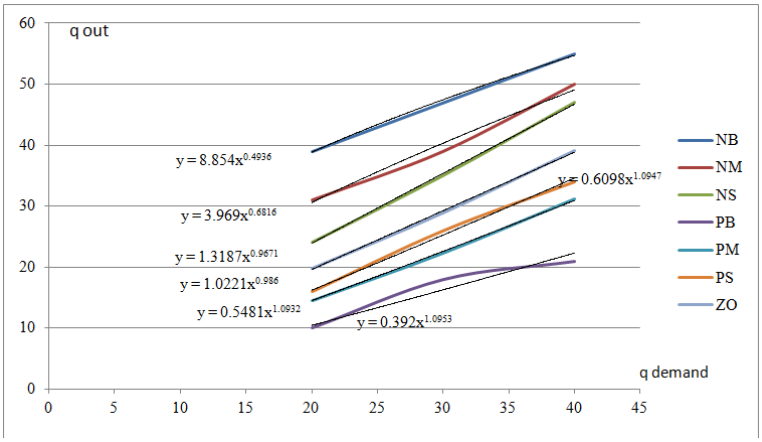


Figure 4: Error range for SGF control system due to linguistic fuzzy variables

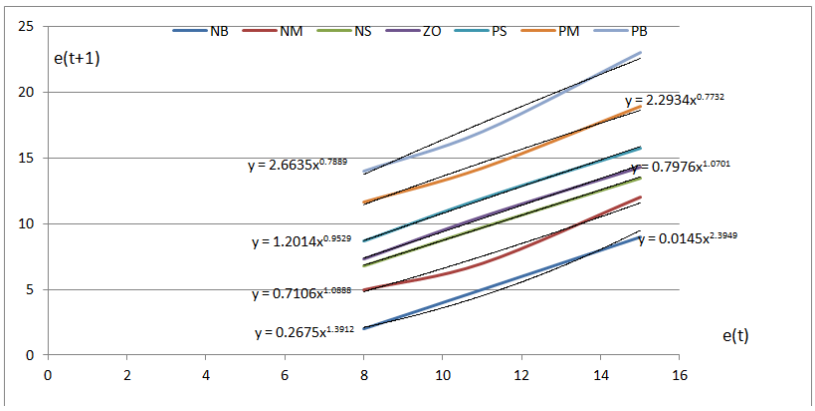


Figure 5: Change error range for SGF control system due to linguistic fuzzy variables

NB: Negative Big *NM: Negative Medium*
NS: Negative Small *ZO: Zero*
PS: Positive Small *Pm: Positive Medium*
PB: Positive Big *B: Design the rules*

1- *IF e is ZO and Δ e(t) is ZO THEN U is Medium*
2- *IF e is PS and Δ e(t) is PS THEN U is increase slowly*
3- *IF e is NS and Δ e(t) is PS THEN U is decrease slowly*

U= [e, Δ e] $\begin{matrix} S1 \\ S2 \end{matrix}$ (Equation 5)

Where

$S1 = \bigvee_{i=1}^{3}\{e \wedge u\}$ (Equation 6)

$S2 = \bigvee_{i=1}^{3}\{\Delta e \wedge u\}$ (Equation 7)

Table 3: Fuzzy Sets for e, Δ e

universe	NB	NM	NS	ZO	PS	PM	PB
-5	1	0	0	0	0	0	0
-4	1	0.5	0	0	0	0	0
-3	0.5	1	0.5	0	0	0	0
-2	0	0.5	1	0.5	0	0	0
-1	0	0	0.5	1	0.5	0	0
0	0	0	0	0.5	1	0.5	0
1	0	0	0	0	0.5	1	0
2	0	0	0	0	0	0.5	0

3	0	0	0	0	0	0	0.5
4	0	0	0	0	0	0	1
5	0	0	0	0	0	0	1

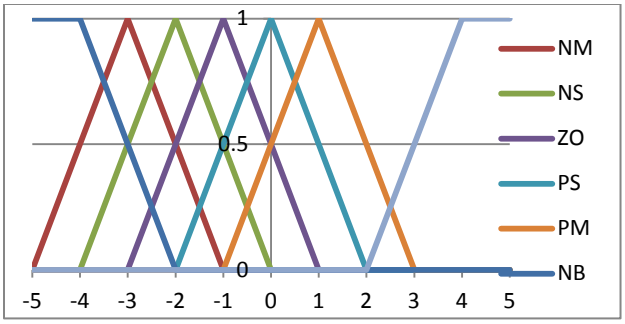


Figure 6: Graph of Fuzzy Sets for e, Δ e

Table 4: Fuzzy Sets for control action (U)

Universe	Decrease	Decrease slowly	Medium	Increase slowly	Increase
1	1	0	0	0	0
2	1	0.5	0	0	0
3	1	1	0	0	0
4	0.5	1	0.5	0	0
5	0	0.5	1	0	0
6	0	0	1	0.5	0
7	0	0	0.5	1	0
8	0	0	0	1	0.5
9	0	0	0	0.5	1
10	0	0	0	0	1
11	0	0	0	0	1

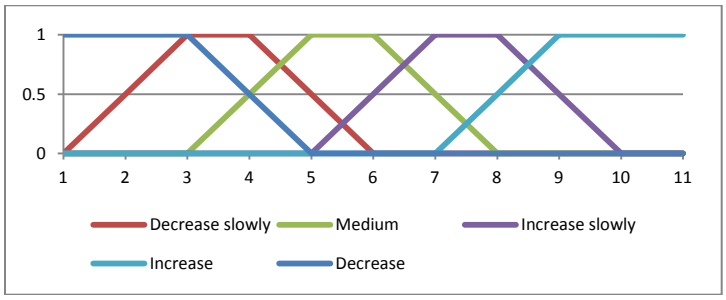


Fig 7: Graph of Fuzzy Sets for control action (U)

$$S1=\begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.5 & 0.5 & 0.5 & 0.5 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.5 & 0.5 & 0.5 & 0.5 & 0.5 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.5 & 1 & 1 & 0.5 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.5 & 0.5 & 0.5 & 0.5 & 0.5 & 0.5 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.5 & 0.5 & 0.5 & 0.5 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$S2=\begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.5 & 0.5 & 0.5 & 0.5 & 0.5 & 0.5 & 0.5 & 0.5 & 0 & 0 \\ 0 & 0 & 0 & 0.5 & 1 & 1 & 0.5 & 1 & 0.5 & 0 & 0 \\ 0 & 0 & 0 & 0.5 & 0.5 & 0.5 & 0.5 & 0.5 & 0.5 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

Case Study:

We suppose that during the operation SGF the q_{demand} is 14 sc m3x109 and the $q_{out(1)}$ is 12.3 sc m3x109 and $q_{out(2)}$ 12.5 sc m3x109 what action should be done?

q_{demand} = 14 sc m3x109

$q_{out(1)}$ = 12.3 sc m3x109

$q_{out(2)}$ = 12.5 sc m3x109

1- Because of the $q_{demand} > q_{out(1)}$ e is Positive ($e(t) = q_{demand}(t) - q_{out}(t)$), so we should define the boundary of it from fig 2

a) $y = 0.392x^{1.095}$ (e= PB), if x= 14 then y = 7.05174 is not possible

b) $y= 0.548x^{1.093}$ (e=PM) , if x= 14 then y= 9.806149 is not possible

c) $y = 0.609x^{1.094}$ (e=PS), , if x= 14 then y= 10.92651 is possible

d) $y = 1.318x^{0.967}$ (e=ZO), , if x= 14 then y= 13.78901 is not possible

Therefore the range of error is PS

2- Because of the e1 > e2 then $\Delta e(t) \leq 0$, so we should define the boundary of it from fig 3

a) $y = 2.663x^{0.788}$ (Δe = NB), if x= 1.7 then y = 0.0498 is not possible

b) $y= 0.267x^{1.391}$ (Δe = NM), if x= 1.7 then y= 0.55 is not possible

c) $y = y = 0.710x^{1.088}$ (Δe = NS), , if x= 1.7 then y= 1.26 is not possible

d) $y = y = 0.797x^{1.070}$ (Δe =ZO), , if x= 1.7 then y= 1.4 is possible

Therefore the range of Δe is ZO

$U= [e, \Delta e]^{S1}_{S2}$

$U= e.S1 \wedge \Delta e.S2$

$$(0,0,0,0,0.5,1,0.5,0,0,0,0).\begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.5 & 0.5 & 0.5 & 0.5 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.5 & 0.5 & 0.5 & 0.5 & 0.5 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.5 & 1 & 1 & 0.5 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.5 & 0.5 & 0.5 & 0.5 & 0.5 & 0.5 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.5 & 0.5 & 0.5 & 0.5 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$(0,0,0,0.5,1,0.5,0,0,0,0,0).\begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.5 & 0.5 & 0.5 & 0.5 & 0.5 & 0.5 & 0.5 & 0.5 & 0 & 0 \\ 0 & 0 & 0 & 0.5 & 1 & 1 & 0.5 & 1 & 0.5 & 0 & 0 \\ 0 & 0 & 0 & 0.5 & 0.5 & 0.5 & 0.5 & 0.5 & 0.5 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

U= (0,0,0,0.5,0.5,0.5,0.5,0.5,0.5,0.5,0,0)= increase slowly

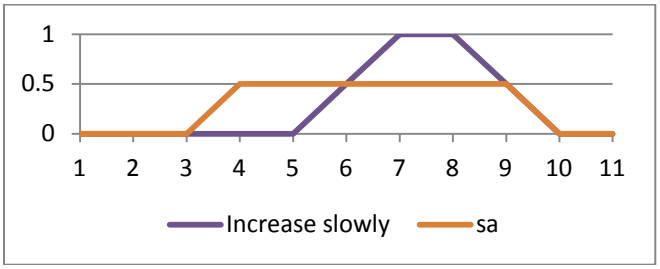


Figure 8: compare calculated result with linguistic description

4- Conclusion

In this paper we presented two fuzzy models for solving the SGF usual problems. For first problem, we design the fuzzy model for multi-objectives decision making to choose the operation strategies in each period of time in life cycle of field. During the operation of SGF, in each period of times, we have some constraints that are imposed by previous period, that should be consider during the decision making. Also we have some objectives that may change during the withdrawal life cycle of field. Hence the model we examine the alternatives for successive time by considering the objectives and weight of them in current time and constraints on next steps. If the result of current strategy cannot support the next period of operation time conditions, we have to change it and try with second ranking result. This model was tested by historical data in 2004, when some problems happened during the operation. This is the new method and in the next step we can do it by software. In second part, we presented the fuzzy model for control the outflow gas rate. In this model first the mathematical equations for each fuzzy linguistic was calculated due to reservoir management team brain storming then the e, Δ e, (acceptable range of error and change error as input data) and the fuzzy control action (as output). The result when compare the calculated result with the linguistic description (fig 8), we found that the quality of fuzzy model is good enough for SGF although there is minor error. These two methods are for the reservoir project management.

References

1. Abedini, R. 2011, “Evaluation of crude oil property using intelligence tool: fuzzy model approach” , Chemical Engineering Research
2. Akhavan, A.n. 2009, Reservoir management challenges in Iranian Petroleum Engineering Industries, Report to NIOC, Tehran, Iran
3. Ching-Hung Wang. 1998, “Integrating Fuzzy Knowledge by Genetic Algorithms” IEEE
4. Ettehadtavakol, A. 2009. “Gas Storage Facility Design under uncertainty”, SPE Journal, 123987
5. HU, B, Mann, G.K.I and Gesine, R.G(1999),” New methodology for analysis and optimal design of fuzzy controls, IEEE Transaction on fuzzy system
6. Lee, C.C. 1990,“ Fuzzy logic in control Systems: Fuzzy logic controller “ IEEE
7. Lee, E.S & Li, R.J, 1993, “Fuzzy multiply objective programming and compromise programming with pareto optimum”. Fuzzy sets and Systems
8. MADAN M. GUPTA, 1986 “Multivariable Structure of Fuzzy Control Systems” IEEE TRANSACTIONS ON SYSTEMS
9. Mamdani , EH (1974), Application of fuzzy algorithm of sample dynamic plant, proc IEE, 121, 1585-1588
10. Maschio, C. 2008, “Production Strategy optimization using Genetic Aigorithm and Quality Map”, SPE Journal, 113483
11. Mihailo Perunicic, (2008), “A model for multistage process unit fuzzy control”, Compute. Ecol. Eng. Journal
12. Otacilio da M. Almeida, (2002), “A Fuzzy Logic Method for Auto tuning A PID controller SISO and MIMO System” 15th Triennial World Congress, Barcelona, Spain
13. Patel, H,K. 2011, “ Application of Genetic Algorithm to Hydrocarbon Resource estimation” , Journal of petroleum and Gas Engineering
14. Pramath Ramaswamy, (1993) “Fuzzy Logic Controller for Nuclear Power Plant” IEEE
15. Ruey-Jing Lian,(1998) “ A mixed fuzzy controller for MIMO systems” Fuzzy Sets and Systems Journal
16. Shokir, E.M. 2009, “A novel model for permeability prediction in uncured wells” , SPE 87038
17. Siemek, J. 2006. “Optimization of the wells placement in Gad Reservoir using SIMPLEX method”, Journal of Science & Engineering
18. Sinayuc,C. & Gumrah, F. 2000, “ Optimization of Energy production from an underground Gas Storage Reservoir” , Energy Sources
19. SOFREGAZ feseability study report for Sarajeh Gas field
20. Solng, H. “Oil Reservoir Production Forecasting with uncertainty estimation using Genetic Algorithms”
21. T. Takagi and M. Sugeno, “Fuzzy Identification of Systems and its Application to Modeling and Control”, *IEEE Transactions on* Systems, Man *and Cybernetics*, Vol. SMC-15, No. 1, pp. 116- 132, January/February 1985.
22. T.R. Rangaswamy , (2006)” Fuzzy Controller for a Gas Turbine Plant”, IEEE
23. Tavakolian, M. 2004, “Production optimization using Genetic Algorithm Approach” SPE Journal, 88901.
24. WU, C.H. 1997, “Statistical and fuzzy infill drilling recovery model for carbonate reservoir” SPE 37728
25. Xavier Litrico, (1998) “Modeling and Robust Control of Dam – river system” IEEE
26. Zadeh, L.A.: 'Fuzzy logic', Computer, Vol. 21, No. 4, pp 83 - 93, April, 1988.
27. Zadeh, L.A.: 'Fuzzy sets', Inform. Contrl., vol. 8, pp 338-353,1965.

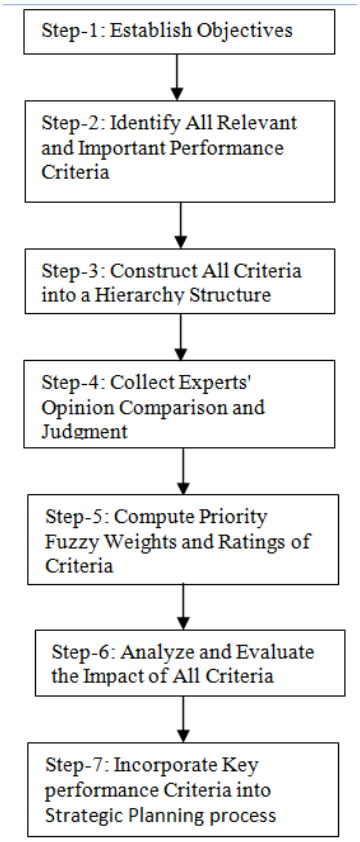
Appendix

First of all, reservoir management team is asked to evaluate the decision criteria and alternatives and to make up a fuzzy pairwise comparison matrix. Then, we derive the fuzzy weight vectors in pairwise comparison matrix by means of geometric mean method. In AHP, all the elements in a pairwise comparison matrix are given as the ratio of inherent weight in each object. Further, de-fuzzification of the weight vectors are implemented. Fuzzy weight vector is converted into the weight vector in crisp values. New comprehensive technique VAM is developed to decide the total ordering of fuzzy numbers. VAM practiced the following process:

(1) Variable axis α is set up. Variable axis depends on both the height of intersection and the modal value of triangular fuzzy numbers to be compared. All the fuzzy numbers are evaluated based on the axis α.
(2) Mapping F is implemented to manage the obtained values as fuzzy numbers.
(3) A fuzzy ranking method is presented based on the extension principle.

(4) The weight vector in crisp values is generated after normalization.

In the end, we obtain final evaluation. All the weight vectors under each criterion are integrated to achieve the evaluation as a group. Flowchart for obtaining the priority vector is described as follows.



Fuzzy AHP process of evaluating alternatives