

NATURAL GAS PIPELINE OPERATIONS OPTIMIZATION VIA MULTI CRITERIA DECISION MAKING

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Abstract

This study aims to find optimum values of three conflicting objective functions namely maximum gas delivery flow and line pack, and minimum operating cost (sum of power consumption), simultaneously.

In this paper, a program, built in Matlab, was used for hydraulic modeling of the pipeline systems (pipes and turbo compressor units). On the other hand, for the optimization part, we use, in this work, the genetic algorithm optimization software NSGA II available in modeFRONTIER by ESTECO.

The decision-maker could privilege his/her own solution based on personal judgment, but in many cases a post processing stage is needed for the purpose of sending to the decision-maker a priority message among the solutions obtained. For this post-processing stage, we use genetic algorithm Multi Criteria Decision Making available in modeFRONTIER by ESTECO.

Key words

Multi criteria decision making, gas pipeline, multi objective optimization.

1 Introduction

In natural gas pipeline operations, the station operator is responsible for making two important decisions: increase or decrease compression in the pipelines, and start-up or shut down of turbo compressor units. Incorrect decisions made by the operator increase energy cost and compressor stations release Greenhouse emissions, specifically carbon dioxide (CO₂) and methane (CH₄) or may cause customer dissatisfaction.

Pipeline operators may face large penalties for deficits capacity below firm contracts. One of the cost effective failure mitigation involves the use of line pack to keep system requirements and delay the effect of system failure impacts. Therefore, maximizing line pack is one of the main objectives for transmission gas pipeline.

A huge volume of natural gas is being transported through the transmission gas pipeline; about 25-50% of the total operating budget of companies is spent on running the compressor stations. Therefore, minimizing the total fuel consumption of the compressor stations is, also, one of the main objectives for transmission networking because of its effects on overall gas operation costs.

This study aims to find optimum values of three conflicting objective functions [Alinia Kashani, and Molaie, 2014] namely maximum gas delivery flow and line pack, and minimum operating cost (sum of fuel consumption), simultaneously.

2 Formulation

The transportation system is defined by the set of all nodes V , the set of all delivery nodes V_d , the set of all arcs A , the set of compressing station arcs A_c and the set of pipe leg arcs A_p [Chebouba and al., 2009].

There are three fundamental objective functions concerning to a gas pipeline network operation expressed as follows:

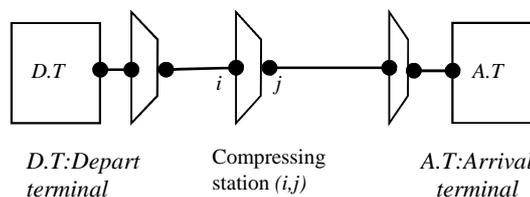


Figure 1: The transportation system

1. *Minimum power consumption* defined by the following objective function:

$$\min \sum_{(i,j) \in A_c} w_{ij} \quad (1)$$

$$w_{ij} = \left\{ x_{ij} \frac{Z_i R T_i}{\omega} \left[\left(\frac{p_j}{p_i} \right)^\omega - 1 \right] \right\} \mu_{ij}^{-1}$$

2. *Maximum gas mass flow delivery* at end-points of the network defined by the following objective function:

$$\max \sum_{i \in V_d} Q_i \quad (2)$$

Q_i : gas mass flow at delivery i ,

3. Line pack maximization

The key consideration in pipeline operations is line pack, which is defined as the volume of natural gas between the compressor discharge pressure and the customer end-point delivery pressure. Line pack maximization is expressed as follows [Alinia Kashani, and Molaei, 2014]:

$$\text{Max} \sum_{ij \in A_{ij}} (LP_{ij}) = \text{Const} \left(\frac{T_{sc}}{P_{sc}} \right) \left(\frac{P_{avg}}{Z_{avg} T} \right) d_{ij}^2 l_{ij}$$

d_{ij} : inlet pipe diameter

l_{ij} : pipe leg length

$$\text{Const} = 7.855 \cdot 10^{-7}$$

All these Objective equations are subject to

$$\sum_{j: (i,j) \in A} x_{ij} - \sum_{j: (j,i) \in A} x_{ji} = B_i \quad i \in V \quad (3)$$

$$p_i^2 - p_j^2 = R_{ij} x_{ij}^2 \quad (i,j) \in A_p \quad (4)$$

$$p_i^l < p_i < p_i^u \quad i \in V \quad (5)$$

$$x_{ij}, p_i \geq 0 \quad (i,j) \in A_c \quad (6)$$

$$\left(\frac{x_{ij}}{n_{ij}}, p_i, p_j \right) \in D_{ij}, n_{ij} \in \{0, 1, 2, \dots, N_{ij}\}, (i,j) \in A_c \quad (7)$$

$$ST_{(i,j)} \in \{0, 1\} \quad (8)$$

At each arc $(i,j) \in A_c$, p_j and p_i are respectively the discharge pressure and the inlet pressure of station (i,j) . P_i^l and P_i^u are the pressure limits at node i , and represent respectively lower limit and upper limit. R_{ij} represents the resistance of pipe leg $(i,j) \in A_p$. For each station (i,j) , x_{ij} , n_{ij} and N_{ij} represent respectively the mass flow rate, the operating turbo compressors number and number of available turbo-compressors in the compressor station (i,j) . The gas compressibility factor Z_i and gas temperature T_i are defined at suction conditions of station (i,j) . μ_{ij} is the turbo-compressor adiabatic efficiency in station (i,j) . The gas constant R and the gas specific heat ratio γ are characteristics of the transported gas. D_{ij} is the feasible operating domain for a single turbo-compressor unit in compressing station (i,j) .

To measure total power consumed by all the pipeline compressor stations, we use (1). Flow balance conservation is given by (3). Equation (4) defines the gas flow dynamics in each pipe leg (i,j) . Constraint (5) bounds the pressure in the pipeline. Equation (6) defines the pressure as nonnegative variable.

Constraint (7) represents the feasible operating domain for a single turbo-compressor unit.

The compressor stations are constituted of several identical turbo compressors, set in parallel, which could be stopped or started. Constraint (8) defines the compressor station status variable as a binary variable.

3. Centrifugal compressor equations

The compressor equations are used to determine whether the operating point is on the compressor map and, if it is, the fuel consumption of the driver (gas turbine). Some parameters are very important for compressor performance, for example inlet volumetric flow rate q_{ij} , speed s_{ij} , adiabatic head h_{ij} and adiabatic efficiency μ_{ij} . For introducing centrifugal compressor characteristics into a pipeline simulation model, it is suggested that the whole head versus capacity map be digitalized and stored as a table. However, a simplified but accurate representation of speed and adiabatic efficiency can be obtained with standard polynomial curve-fit procedure for each centrifugal compressor [Walton, 1986]; the relationship among these quantities can be well described by the following equations:

$$\frac{h_{ij}}{s_{ij}^2} = A_H + B_H \left(\frac{q_{ij}}{s_{ij}} \right) + C_H \left(\frac{q_{ij}}{s_{ij}} \right)^2 + D_H \left(\frac{q_{ij}}{s_{ij}} \right)^3 \quad (9)$$

$$\mu_{ij} = \left(C_E \left(\frac{q_{ij}}{s_{ij}} \right)^2 + B_E \left(\frac{q_{ij}}{s_{ij}} \right) + A_E \right) / 100 \quad (10)$$

where A_H , B_H , C_H , A_E , B_E and C_E are constants which depend on the compressor unit and are typically estimated by applying the least squares method to a set of collected data of the quantities q_{ij} , s_{ij} , h_{ij} et μ_{ij} . Four other parameters are frequently provided: they are minimum speed s_{min} , maximum speed s_{max} , surge limit 'surge' and stonewall limit 'stonewall'.

These give the limits to the speed s_{ij} and the ratio q_{ij} to s_{ij} , i.e.,

$$S_{min} < S_{ij} < S_{max} \quad (11)$$

$$\text{Surge} < \frac{q_{ij}}{s_{ij}} < \text{Stonewall} \quad (12)$$

The inequalities (11) and (12) together with equation (9) constitute a feasible operating domain for the unit. Since, the preferred variables from the pipeline modeling perspective are mass flow rate x_{ij} , suction pressure p_i and discharge pressure p_j , the relationships between (h_{ij}, q_{ij}) and (x_{ij}, p_i, p_j) are the following:

$$\begin{aligned} h_{ij} &= \frac{Z_i R T_i}{\omega} \left[\left(\frac{p_j}{p_i} \right)^\omega - 1 \right] \\ q_{ij} &= Z_i R T_i \frac{x_{ij}}{p_i n_{ij}} \\ \omega &= \frac{\gamma - 1}{\gamma} \end{aligned}$$

The specific heat ratio γ , the gas compressibility factor at suction conditions Z_i , and the gas constant R , are positive parameters, n_{ij} is an integer number which represents the number of compressor to put in service.

Figure 2 shows the set of data collected from a typical centrifugal unit. In this figure, we plot H vs. Q , showing the control lines for s (between s_{min} and s_{max}) and Q/s (between surge and stonewall),

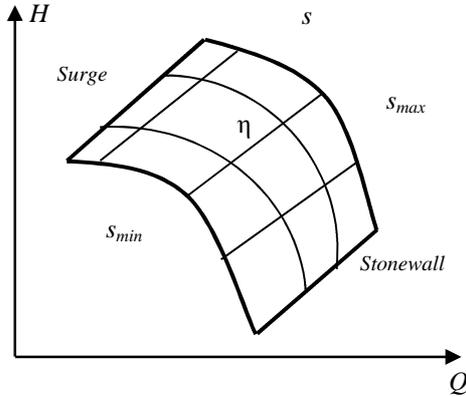


Figure 2: Operation Envelope in Q , s , and H

4 Non-dominated sorting genetic algorithm (NSGA-II)

In NSGA-II [Deb and al, 2002], we first create the offspring population Q_t (of size N) using the parent population P_t (of size N), as shown in fig. 3. The usual genetic operators such as single-point crossover and bit-wise mutation operators are used in this process. Next, we combine the two populations to form an intermediate population R_t of size $2N$. After that, we evaluate the fitness of each offspring in the $2N$ population using the multiple objective functions. At this stage, we carry out non-dominated sorting procedure over the $2N$ population to rank and divide the individuals into different non-dominated fronts (F_1, F_2, F_3, \dots).

After that, we create the new parent population P_{t+1} by choosing individuals of the non dominated fronts, one at a time. We select the individuals of best ranked fronts first followed by the next-best and so on, till we obtain N individuals. As the intermediate population R_t has a size of $2N$, we discard those fronts which could not be accommodated. In case there is space only for a part of a front in the new population, we use a crowded distance operator to determine the individuals among those in the front that are from the least crowded regions. We select such individuals so as to pack up the required number in the new population P_{t+1} [Rio, and al., 2010].

5 Software

These equations were integrated in a computer program, built in Matlab. This program was used for hydraulic modelling of the pipeline systems (pipes and turbo compressor unit). The model simulates the steady-state gas flow in a pipeline network.

On the other hand, for the optimization part, we use, in this work, the genetic algorithm optimization software NSGA II available in modeFRONTIER by ESTECO .

Combinations of a computer program, built in Matlab, and NSGA-II was accomplished using specific input and output file (Fig. 4).

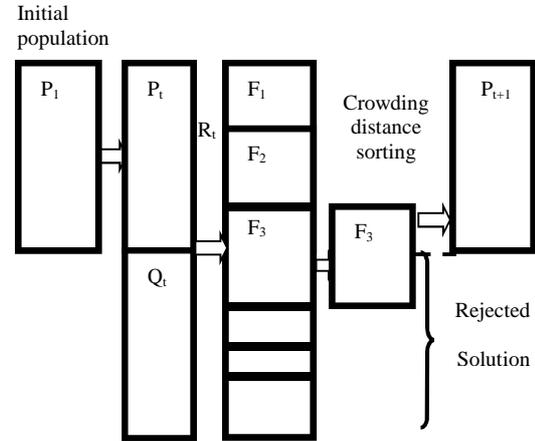


Figure 3. Operating Principle of NSGA-II

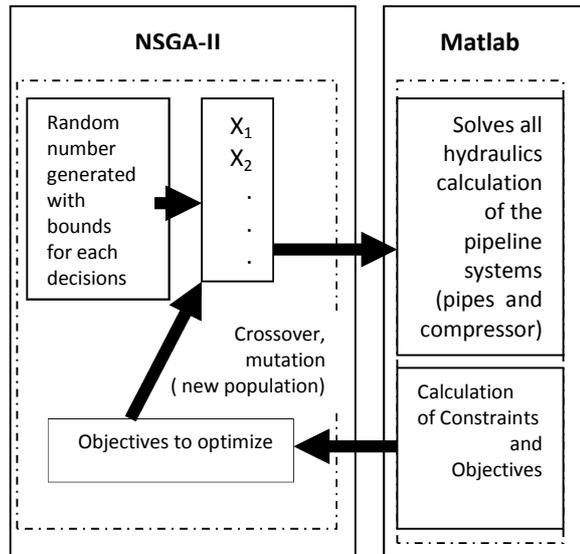


Figure 4. NSGA-II and Matlab Combination

NSGA-II allows optimization analysis to be achieved by changing the values assigned to the input variables of Matlab software. The output from Matlab software can then be described as the objectives and constraints of the problem.

The three objective functions as mentioned before are:

- Minimizing the consumed power used by turbo compressors,
- Maximizing Line pack ,
- Maximizing gas mass flow delivery at end-points of the network.

The final output of NSGA-II is a set of solutions (known as a Pareto front) in which each solution is

better than the others in at least one of the objective functions.

The decision-maker could privilege his/her own solution based on personal judgment, but in many cases a post processing stage is needed for the purpose of sending to the decision-maker a priority message among the solutions obtained. This post-processing stage is generally absent in the papers concerning gas transport system multi-objective optimization. In this paper, we use genetic algorithm MCDM available in modeFRONTIER by ESTECO.

6 Case studied and results

Gas transmission network considered in this paper, consists of two parallel pipelines of total length more than 1000 km. Natural gas flows from In Amenas to Hassi R'mell in the south of Algeria (GR1-GR2 gas pipeline). The gas is transported with the help of five compressor stations. Each compressor station consists of a number of compressors (up to four).

In this paper, NSGA-II is applied by considering the following decision variables: compressor station discharge pressure, number of running turbo-compressors, compressor station status and gas flow rate at injection points.

The options used for implementing NSGA-II are population size = 10, maximum number of generations = 10000, cross probability of 0.9 and mutation probability of 0.1.

The optimization problem is solved and the results are the Pareto front points (fig.5) for gas mass flow delivery maximization vs. power minimization vs. line pack maximization.

Applying the genetic algorithm MCDM available in modeFRONTIER by ESTECO to the values reported in the pareto front, the ten first ranked solutions are the ones shown in table 1.



Figure 5. Pareto front

| Ranked solutions | Criteria | | |
|------------------|---|---------------------|------------------------------|
| | gas mass flow delivery (Sm ³ /day) | consumed power (kw) | Line pack (Sm ³) |
| 1 | 92075533 | 181079 | 14109206 |
| 2 | 92075531 | 184987 | 14109206 |
| 3 | 92075491 | 180595 | 14109210 |
| 4 | 92075397 | 181078 | 14109219 |
| 5 | 92075391 | 181078 | 14109219 |
| 6 | 92075323 | 181077 | 14109225 |
| 7 | 92075309 | 181077 | 14109227 |
| 8 | 92075282 | 180727 | 14109225 |
| 9 | 92075256 | 180593 | 14109232 |
| 10 | 92075248 | 180594 | 14109232 |

In tables 2 and 3, we present, in the case of the best solution, the optimal policy of the gas pipeline operation obtained by the proposed method.

These tables present detailed output data (decision variables) for the five compressor station operation regimes.

| | CS1 | CS2 | CS3 | CS4 | CS5 |
|-----------|-----|-----|-----|-----|------|
| Pd | 72 | 72 | 72 | 72 | 70,2 |
| ST | 1 | 1 | 1 | 1 | 1 |
| NC | 1 | 3 | 2 | 2 | 3 |

CS X: Compressor station X

NC: Number of compressor units in service

Pd: Compressor discharge pressure in bars

| Injection points | gas flow rate(Sm3) |
|------------------|--------------------|
| Injection 1 | 1.50E+07 |
| Injection 2 | 2.97E+07 |
| Injection 3 | 2.49E+07 |
| Injection 4 | 7556066 |
| Injection 5 | 1.47E+07 |
| Injection 6 | 9967570 |

7 Conclusions and Recommendations

This paper presents an application of the genetic algorithm MCDM available in modeFRONTIER by ESTECO to rank the non-dominated solutions originated by the multi-objective optimization of a gas pipeline operations solved through the NSGA-II method.

We can provide a decision aid tool to operators of gas pipeline networks for making appropriate decision to determine discharge pressures and number of turbo compressors to put in service.

This optimal planning of the functioning of turbo compressor units we allows for significant gains in consumed power, it also allows us to reduce CO2 emissions into the atmosphere.

In the future, to improve these results, we plan to use a hybrid method combining the genetic algorithm optimization software NSGA II and a local search.

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