MULTI-OBJECTIVE OPTIMIZATION OF BOTH PUMPING ENERGY AND MAINTENANCE COSTS IN OIL PIPELINE NETWORKS USING GENETIC ALGORITHMS

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Keywords: Pump operation scheduling, Multi-objective genetic algorithm, Non-dominated sorting genetic algorithm, Oil pipeline networks, Power optimization.

Abstract: This paper proposes an optimization model for the pipeline operation problem using a dual-objective non-dominated sorting genetic algorithm (NSGA-II). One and foremost objective is to minimize pumping energy costs. The second objective is to recognize the pipeline operators' concern on pumps maintenance costs by reducing the number of times pumps are turned on and off. This is commonly believed as a main source of wear and tear on the pumps. The formulation of the problem is presented in detail and the model is tested on a hypothetical case study (which is based on consultation with two industrial partners). The output results are promising since they would give operators a better understanding of different optimal scenarios on a "Pareto front". Operators can visually assess several alternatives, and analyse the cost-effectiveness of each scenario in terms of both objective functions.

1 INTRODUCTION

Oil is commonly transported using pipelines by the propulsion from centrifugal pumps powered by either electricity or gas. Pumps are located along the pipelines at the approximate interval of 20 to 100 miles, depending on the geography and size of the pipelines, and also capacity requirements. Finding the optimal operation policy (regime) of oil pipelines is challenging due to change prone energy cost structures and complex hydraulic models that pose distinct challenges to the optimization analysis (Webb, 2007). The pipeline-operation optimization problem is known as a mixed-integer non-linear optimization problem due to constraints dictated by pipelines non-linear hydraulic model (Lindell et al., 1994).

Oil distribution systems consist of components such as reservoirs, pipes, pump stations, and valves. Pipes carry the fluid(s) from reservoirs to the designated delivery points, e.g., refineries, or ports. Pumps provide pressure needed to overcome gravity and pipe friction. Valves are in charge of controlling flows and pressures. The entire operation is expensive, due to the fact that usually large masses of fluid are to be pumped. However, significant savings can be achieved through efficient energy management, by matching pumping schedules with time and shifting heavy pumping to periods with cheap tariff rates (e.g., night time) (Webb, 2007).

The objective of a pumping optimization problem is to provide the operator with the least-cost operation policy for all pump stations in the pipeline distribution system while maintaining the desired delivery schedule. The operation policy for a set of pumps is simply a schedule that indicates when a particular (fixed-speed) pump or group of pumps should be turned on or off over a specified period of time, and the setting of the operating speed in case of variable-speed pumps. The optimal policy attempts to result in the lowest total operating cost subject to a given set of boundary conditions and system physical and operational constraints (Lindell et al., 1994).

This paper proposes an optimization model based on Non-dominated Sorting Genetic Algorithm (NSGA-II) (Deb, 2001) for finding optimal pump operation schedule. The two objective functions are: (1) minimizing the cost of electric energy used by pumps, and (2) minimizing the number of pump on/off switching, which is a conventional surrogate measure of pumps maintenance cost (Meetings mi-

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The final output of NSGA-II is a set of solutions (known as a Pareto front or Pareto set) in which each solution is better than the others in at least one of the objective functions. The Pareto set could be used by an operator to recognize the trade-offs of sacrificing an objective in favour of another. For instance, in the case of our problem, the operator can visually assess the energy cost effectiveness obtained by several extra pump switching. This way, he/she can make a better decision on to whether toggle a pump status, which causes wear on the unit, or operate the system with a higher cost.

The remainder of the paper is outlined as follows. Section 0 reviews the related works on the problem of pump operation scheduling. The mathematical definition of the objective functions and constraints are thoroughly discussed in Section 0. Section 0 explains the basic concept of NSGA-II, which is chosen as our solution methodology. The model is applied to a hypothetical pipeline network and the results are presented in Section 0. Sensitivity analyses of the case study are discussed in Section 0. Finally, Section 0 concludes the paper and discusses some of our future works directions.

2 RELATED WORKS

The problem of pipeline operation optimization has been a subject of study in three major areas: (1) water distribution networks, (2) natural gas transmission pipelines, and (3) oil products transmission pipelines. Although each of these networks has its own characteristics in terms of fluid behaviour, contract terms, network size, structure and elements, but the general idea that forms the backbone of formulating these problems remains similar.

In (Solanas and Montolio, 1987), dynamic programming (DP) was used to evaluate the optimal pumps operation scenario. However, for practical distribution networks comprising more pump units that should be evaluated in longer time frames, application of dynamic programming (DP) needs extensive computational resources due to the ‘curse of dimensionality’. This problem limits the application of all dynamic programming-based techniques to large-sized networks.

Zessler and Shamir (Zessler and Shamir, 1989) used the method of progressive optimality which is an iterative DP. Jowitt and Germanopoulos has proposed a method based on Linear Programming (LP) in (Jowitt and Germanopoulos, 1992) and have linearized the formulations. However, any linearization of the formulations would lead to linearization errors.

Lansey and Awumah have considered pump switching as an additional constraint in their optimization model in (Lansey and Awumah, 1994) which accounts for the hardly-quantifiable maintenance costs. They have adopted a two-level approach which is compromised of a pre-optimization level as well as the actual optimization step.

Ulanicki et al. (Ulanicki et al., 2007) presented a dynamic optimization approach to solve the optimal pump scheduling problem. The model is claimed to be faster than other existing approaches and follows a two-stage approach in finding the solution.

Aligned with the trends of other optimization problems, recent efforts are conducted to implement the pump scheduling optimization using heuristic and meta-heuristic approaches such as ant colony (Ostfeld and Tubaltzev, 2008), particle swarm (Wegley et al., 2000), or genetic algorithms (Ilich and Simonovic, 1998).

In (Ostfeld and Tubaltzev, 2008), both design and operation aspect of the pipeline system have been modeled simultaneously in order to find the optimal design of the network. In (Ilich and Simonovic, 1998), a search within the feasible region has been used which is claimed to improve the efficiency in comparison with conventional Genetic Algorithm (GA) method. The method has been tested on a hypothetical network having five serial pumps.

Zhang in (Zhang, 1999) couples GA with a transient-hydraulic simulation model to generate and evaluate trial pipe networks designs in search of an optimal solution. The developed approach has been applied to the New York City’s water supply tunnels.

A great number of research works has also been conducted for pipeline scheduling problem in the gas pipelines sector. The problem was formulated with GA and implemented in the Pascal programming language by Goldberg in (Goldberg, 1987a) and (Goldberg, 1987b). Wright and et al (Wright et al., 1998) applied simulated annealing for finding the optimum configuration and power settings for single compressor problem as well as multiple compressors arranged in series with constant pressure drops in the segment. In (Betros et al., 2006), a genetic algorithm is developed to optimize operation of gas pipeline networks. Mora in (Mora, 2008) proposes a multi-agent cooperative search technique to optimize the operation of large and complex natural gas pipeline networks.

Albeit oil pipeline stations are accounted as a very important category of pipelines, but very few research works have been devoted to this area. This might be due to the fact that most of the research in this area relates to corporate closed-source software development projects which mostly do not appear in publications and, ultimately prevents third parties from analyzing or reusing the details of the solution methods developed (SSI, Last Viewed: April 2010).

In (Veloso et al., 2004), a spreadsheet-based computational tool was used to reduce the energy consumption at each pumping station in oil pipelines. Firstly, all possible pumping arrangements are related to viable flow rates of the pipeline under consideration. Then, a hydraulic simulator is used to calculate the cost of each arrangement. All the cost values are imported to a spreadsheet, which will be used for selecting the minimum operation arrangement by the operators as needed. This method was applied to a 3 pipeline station network and sounds memory and time intensive for larger networks. Also, this "snap-shot" optimization procedure does not guarantee that the set of pump arrangements over a time period gives the minimum cost. In (Abbasi and Garousi, 2010), a mixed-integer linear formulation for finding optimal pump operation schedule for oil pipelines is introduced. The nonlinear equations have been linearized in small operational flow rate ranges so that the linearization errors are as marginal as possible. The proposed formulation is capable of identifying the most cost-effective solution to the linearized format of the problem by giving the operation regime with the lowest-cost energy consumption that satisfies the mandatory operational and physical constraints given a set of time-varying and quantity-varying electricity tariffs. The formulation is then implemented in the GAMS toolset and tested on a hypothetical network.

This paper builds on top of the previous efforts conducted in this area by considering multi-objectives for the oil pipeline operation scheduling problem which enables the operators to better compare the cost effectiveness of the two objectives. To the best of the authors' knowledge, no existing article has attempted considering these two objectives at the same time.

3 MATHEMATICAL FORMULATION

Implementation of any optimization problem calls for a due assessment of the formulation constructing the model. In this section, the pipeline operation problem has been defined. The constraints and objective functions of the problem have been formulated and explained based on the relevant input parameters and decision variables.

3.1 Problem Definition

The optimal operation of oil pipeline networks involves selecting pumps' operational schedules that provide the least operational cost and also least maintenance costs, while satisfying the system constraints over a given finite time horizon. The key components of the pump scheduling problem are network hydraulics model, operational constraints, and the objective functions.

3.2 Decision Variables

Depending on the system characteristics and time window that the system is being modelled in, the decision variables can vary in many forms. In the case of this paper, the first set of decision variables defined is the set of binary variables to indicate the on/off status of the pumps at each time step.

The speed of the pump, in case of the variable-speed pumps, is another decision variable.

3.3 The Two Objective Functions

The first objective function is to minimize the total cost of electricity used by pumps in the whole operation period. The second objective function is to minimize the number of pumps switching (on to off, or off to on) (Lindell et al., 1994). Each of these objective functions is discussed and formulated next.

3.3.1 Objective Function 1: Minimization of Total Electricity Cost used by Pumps

The most important objective function of the pipeline operation scheduling problem represents the total operating cost to be minimized. It is usually comprised of energy cost for all of the pump units in the whole operation period. Although other costs such as penalties for deviation from the final delivery contract might be considered, in this paper the delivery contract has been considered as an operational constraint of the system.

Pumping cost is evaluated based on the electricity power tariff over the pumping duration. Two types of electricity charging patterns are usually used in the industry (Prindle, Last Viewed:

April 2010):

- fixed electricity price rate;
- time-variable or quantity-variable electricity price rate;

Due to the fact that the latter case is more general, this pricing pattern has been considered in this paper.

Also, it has to be noted that the oil pipelines are usually expanded over a reasonable geographical area, and they usually enter into contracts with several local electricity providers for their electricity needs. In this context, oil pipeline operators face various electricity purchasing contracts. Some companies offer incentive prices for electricity usage to sell more electricity while, on the other hand, some others encourage their customers to consume less electricity (Meetings minutes, Spring and Fall 2009).

Some utilities encourage customers to limit their consumption within a specific limit. Although any nonlinear function of the consumed power and cost is possible to be considered in GA models; however, in this paper, it is considered that rate of electricity follows the trend presented in Figure 1, which is a generic case.

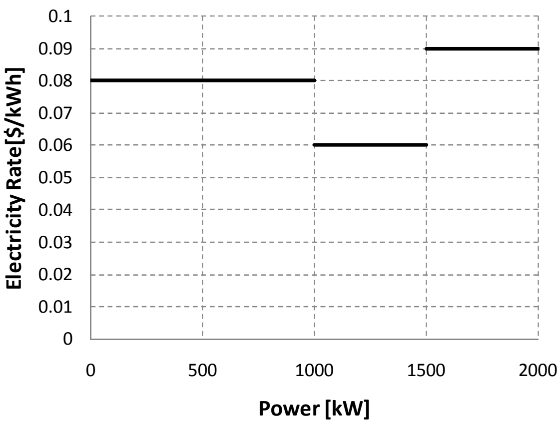

Figure 1: Electricity Rates.

Power system companies are interested to have a smooth load profile. This helps them in better planning and scheduling of the power plants operation to generate electricity by their highest efficiency and also making use of the existing transmission network close to nominal limit. Due to these facts, usually power system providers consider lower rates for the hours of the day that other industrial sectors are off and lower consumption of electricity is expected, which usually happens to be around midnight.

In the case study reported in this paper, by reviewing some example power contracts from our industrial partner, it is assumed that the electricity rate of daytime is twice the nighttime rate. It is noteworthy that using genetic algorithm or any other evolutionary algorithm as the solution technique, any multiple segments and any type of cost evaluation method could be modeled. Even any nonlinear relationship between the electricity cost rate and power consumption could be considered. This is a significant feature of genetic algorithms compared to more systematic approaches (e.g., LP, MILP) on solving this problem which stems from the flexibility of evolutionary algorithms in general.

Based on the aforementioned formulations, the pumping cost objective function could be stated in mathematical terms as:

$$\min \quad \left\{ \sum_{i=1}^{t} \sum_{j=1}^{J} Cost_i^t (P_i^t) \right\} \tag{1}$$

In which, P^t_j is the power consumed by pump j at time step t and is a function of pumps pressure, flow rate passing, its operating efficiency and the fluids characteristic which is constant. Note that the full list of mathematical notations defined and used in this article can be found at the end of this article.

The following equation calculates the power needed to operate the pump (Boulos et al., 2006):

$$P_i^t = \frac{\gamma \times Q_i^t \times PH_i^t}{\eta_i} \tag{2}$$

In the above equation, the terms flow, pressure and efficiency are not independent. Technicians usually consult empirically driven curves to find out the operating status of a specific point. However, in order to formulate the problem, an explicit relationship between power and the other variables is needed.

According to experiments conducted by mechanical engineers (Boulos et al., 2006), the power consumption of a pump could be determined as a function of two independent variables of pump's speed and the flow rate of the fluid passing by it. According to (Ulanicki et al., 2008), a polynomial equation as stated in Equation (3) best fits the empirically-extracted pump curves.

$$P_i^t = a_j \times Q_j^{t\,3} + b_j \times Q_j^{t\,2} \times s_j^t + c_j \times Q_j^t \times s_j^{t\,2} + d_j \times s_j^{t\,3} \tag{3}$$

3.3.2 Objective Function 2: Minimization of the Number of Pump State Changes

Another important cost issue that deserves consideration is pump maintenance. An operation schedule in which pumps are turned on and off very frequently may reduce energy consumption; however, this schedule may increase the wear and tear on the pumps and increase the resulting pump maintenance costs. It would also complicate the operation of the system from the operator's point of view, i.e., the human operator has to constantly review the operation schedule and turn the pumps on and off. This task itself can be error prone and also risky from system stability point of view.

The exact amount of maintenance costs is not easily quantifiable, but it can be assumed that it increases as the number of pump change status increases. Hence, the number of pump change status is used as a surrogate measure for the intangible wear-and-tear maintenance costs. Therefore, the switching objective is introduced into the model as the second objective function. The operators can then evaluate the trade-off of increasing cost to reduce the number of switching by assessing the model results.

This second objective function is formulated as the following:

$$\min \left\{ \sum_{j=1}^{J} \sum_{t=1}^{T-1} \left| Bp_j^{t+1} - Bp_j^t \right| \right\} \tag{4}$$

In which, the absolute difference between the binary variables associated with the status of a specific pump in two successive time intervals is summed up over the entire time horizon and for all the pump units. The final result is the number of all pumps status changes seen in the analysis period.

3.4 Constraints

The search space for pipeline scheduling problem, as mentioned earlier, is confined by a number of constraints. Based on the technical aspects, these constraints can be divided into two categories: (1) hydraulics constraints, and (2) operational constraints.

The hydraulic-model constraints stem from natural behaviour of a fluid being transported in a pipeline. These constraints validate the feasibility of the model in sense of the relationship between the primary state variables of the hydraulic model.

On the other hand, the operational constraints account for the tolerance of the equipments or in concise, their operation limits, as well as the constraints imposed by contracts or any other external cause.

The mathematical equations representing the aforementioned constrains are being discussed in the next sub-sections.

3.4.1 Hydraulic Constraints

When assessing a particular pump-operating policy, it is essential to make sure that the hydraulic state variables of the model match their natural connection couched in mathematical equations. Any fluid movement in a pipeline network entails satisfying the two fundamental laws of conservation of mass and conservation of momentum (Mennon, 2005).

The conservation of mass law for non-compressible fluids, as the name implies, states that a balance exists between the summation of the masses entering and exiting at any point on the pipeline at a specific time instance. Equation (5):

$$Q_{i,In}^t - Q_{i,Out}^t = 0 \qquad \forall i,t \tag{5}$$

The conservation of momentum which is based on the conservation of energy law, establishes a relationship between the pressure generation and losses in the pipeline. For any two successive pressure points, the differences in absolute head (pressure) is equal to the net head added to the system by pumps (if there's any) minus the head lost in either valves or segment's friction loss due to the movement of the fluid.

Difference in the altitude of the according locations also contributes to the equation as static heads. Equation (6) indicates the conservation of momentum law (Mennon, 2005).

$$\begin{gathered}\left(H_q^t - HS_q^t\right) - \left(H_p^t - HS_p^t\right) = PH_j^t - PL_j^t - V_j^t \qquad \forall j,t \\ p,q \in \{nodes\ being\ connected\ by\ segment\ \ j\}\end{gathered} \tag{6}$$

The term PL_j^t is the pressure loss that occurs in pipeline segment j at time instant t as a result of friction which depends on the fluid type, pipeline material and cross section, and the flow rate passing the segment. This loss could be quantitatively evaluated by the Darcy-Weisbach equation (Tullis, 1989) as follows:

$$PL_j^t = CL_j \times \left(Q_j^t\right)^2 \qquad \forall j,t \tag{7}$$

Since valves control high pressures, they appear in Equation (6) accompanied by negative sign. The last term of the Equation (6), PH_j^t, represents the pressure head added to the system by the pump located on segment j at time t. The pumps head is a function of the flow rate and also the speed of the pump in case of variable speed pumps. The head-flow rate characteristic curve of a variable speed pump is usually provided by the manufacturer for a specific speed. A typical head/efficiency versus flow rate curve of a variable-speed pump is presented in Figure 2.

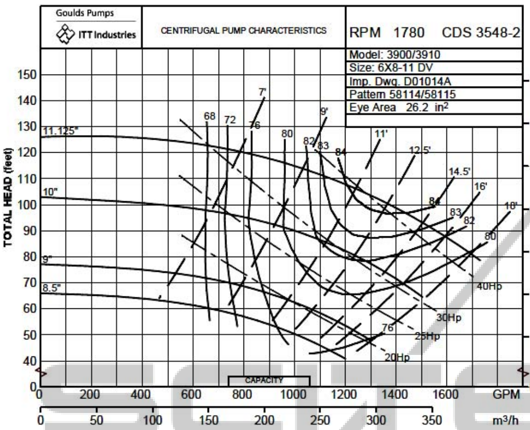

Figure 2: A typical head/efficiency versus flow rate curve. Taken from (Goulds Pumps, Last Viewed: March 2010).

The head versus flow rate curve is often approximated by a quadratic polynomial (Ulanicki et al., 2008) as:

$$PH_j^t = AP_j \times Q_j^{t2} + BP_j \times Q_j^t \times S_j^t + CP_j \times S_j^{t2} \qquad \forall j,t \tag{6}$$

3.4.2 Operational Constraints

Beside the basic hydraulic constraints that lay the groundwork for implementing the model, a multitude of operational constraints exist to propel the solution towards an operational range. These constraints generally originate from equipments' operation limitations. Also, contract-related constraints or environment-related constraints are considered to fall in this category.

The pipeline wall is prone to cracks and leaks if it is operated under high pressures. This not only causes serious damages to the pipe but also, flow of oil products to the environment causing environmental damages which is followed by considerable penalties. Hence, it is essential that the operators keep the pressure of the nodes especially on junctions lower than a threshold. On the other hand, low pressure in the pipeline causes formation of cavities in the fluid which causes corrosions on the pipeline wall. More severely, these cavities form a two phase flow, which seriously damages the impellers of centrifugal pumps. The two mentioned constraints are expressed in Equation (7).

$$H_i^{\min} \le H_i^t \le H_i^{Max} \qquad \forall i,t \tag{7}$$

Furthermore, the flow rate of the pipeline should be bound to a certain limit, for high flow rates' friction with pipeline wall causes overheat of the pipe and product. This constraint is indicated by Equation (8).

$$0 \le Q_j^t \le Q_j^{Max} \qquad \forall j,t \tag{8}$$

The speed of rotation of the pump units are bounded by an upper and lower limit as stated by the following equation:

$$S_j^{\min} \times B_j^t \le S_j^t \le S_j^{Max} \times B_j^t \qquad \forall j,t \tag{9}$$

Note that the binary variable B_j^t sandwiches the upper and lower bounds to zero at the times the pump is off.

Finally, delivery contract imposes the most prominent constraint on the problem. The pipeline operator is supposed to deliver a contracted volume of the product to the designated delivery points by the end of the planning time period. Hence, the summation of the volume of the fluid being delivered to specified locations in every time step should be more than or equal to the contracted amount for that specific location. The corresponding equation to this constraint is as follows:

$$\sum_{t=1}^{T} QSink_i^t \ge Con_i \qquad \forall i \tag{10}$$

4 SOLUTION METHODOLOGY

The Fast Non-dominated Sorting Genetic Algorithm (NSGA-II) is a very popular approach in MOGA, as it has been used in many existing works such as (Kang et al., 2009) and (Baran et al., 2005). Thus, it was also chosen to be used in this work. Efficient sorting and ability to maintain a diverse set of elite population could be counted as features of NSGA-II (Deb, 2001).

5 CASE STUDY

To evaluate our optimization technique, we are working with a Western Canadian oil pipeline operator to apply our optimization technique to its pipeline network. However, as of this writing, extraction of actual parameters to be able to execute the algorithm has not been completed yet.

In the mean-time, we evaluate the proposed approach on a hypothetical oil distribution system comprising of 5 pipeline segments which connect 6 nodes. The system is designed to feed two delivery nodes from a single source on a dendritic structure. All of the segments are equipped with pump units and valves. Structure of the network is shown in Figure 3. It has been assumed that the whole assessment timeframe is one day comprising three time-of-use electricity tariffs, in which the cost of the last time period is half of the cost of the other two. The parameters of this hypothetical test system could be found in the Table 1. The formulation of this hypothetical system results in 62 decision variables and 48 constraints.

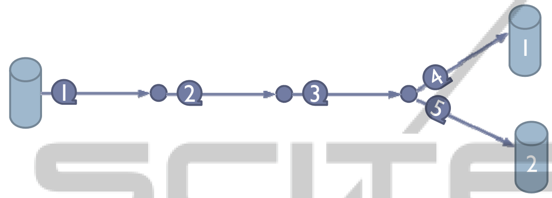

Figure 3: Configuration of the test case pipeline network.

It should be noted that the formulation structure is generic and any number of sources and delivery points and also branches could be considered easily.

Table 1: Parameters of the hypothetical test system.

CL_j	0.3	S_j^{min}	0.2
Con_i i=4,5	60	S_j^{Max}	2.5
H_i^{min}	300	AP_j	2.3×10^{-6}
H_i^{Max}	1000	BP_j	8.3
Q_j^{Max}	100	CP_j	4.6×10^{-3}
a_j	7.4×10^{-3}	c_j	5.7×10^{-7}
b_j	1.66	d_j	3.6×10^{-3}
SH_i	0	Electricity Rate 1	0.08
Electricity Rate 2	0.06	Electricity Rate 3	0.09
Change Rate Value 1	1000	Change Rate Value 2	1500

In order to investigate the ability of NSGA-II dealing with pipeline operation optimization problem, a MATLAB program was developed. The GA parameters set for the algorithm is presented in Table 2. These parameters were empirically calibrated and were found as suitable parameters after a series of experimental runs, using ideas from the work of (Garousi, 2008).

By running the MATLAB program in MATLAB version 2009a, the Pareto front depicted in Figure 4 was generated. Due to the random effects of GA, we executed the MATLAB program for 50 times and the average execution time of each run on a PC with Windows Vista, a 2.30 GHz CPU, and 2 GB of RAM was 885.36 seconds (about 15 minutes).

As it could be seen from the Pareto, higher cost of operation comes with zero switching while the case with three switching is the operation scenario with the lowest cost. Noteworthy, the amount of operation cost reduction is reasonable between having one switching and no switching state. Also, this amount is not negligible between having one switching and two switching while no reasonable cost reduction is achieved for the case of three pump switching. Pipeline operators can make decisions based on such Pareto to visually identify the trade-offs of operations with low costs.

Table 2: Calibration of GA parameters.

Parameter	***Value***
Population size	315
Number of Generations	100
Crossover Rate	80%
Mutation selection strategy	Gaussian

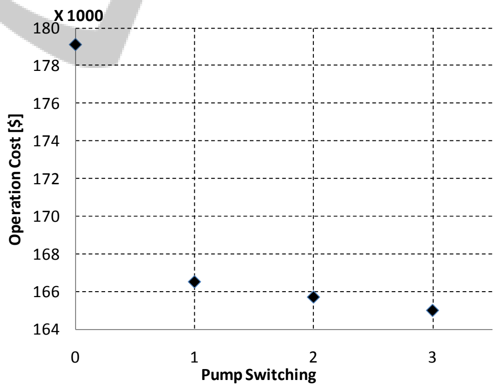

Figure 4: Four solutions on the optimal Pareto-front of the test case problem.

Table 3 and 4 present detailed output data (decision variables) for two of the four pump operation regimes. It should be noted that the pressure reduction by valves of the network are managed to be zero in all combinations. The first pump is always running in order to add enough pressure to compensate for the loss of the first line segment. Similarly the second pump is always ON to add enough pressure for the fluid to pass through the pipeline.

Table 3: The pump operation schedule (speed values) for zero switching.

Pump	*Period 1*	*Period 2*	*Period 3*
1	2.4	2.4	2.4
2	1.7	1.7	1.7
3	0	0	0
4	0	0	0
5	0	0	0

* Operation Cost = $179,110.00

Table 4: The pump operation schedule (speed values) for one switching.

Pump	*Period 1*	*Period 2*	*Period 3*
1	2.4	2.4	2.4
2	0.9	0.9	0.77
3	0	0	0.43
4	0	0	0
5	0	0	0

* Operation Cost = $166,500.00

6 SENSITIVITY ANALYSIS

In order to assess the effect of variation of GA parameters on the performance of the model, several sensitivity analyses were conducted, as discussed next.

6.1 Population Size

The population size of the solutions has been changed from 10 to 500 in the increments of 50. The optimization results for the amount of cost for the second objective of 3 switching have been presented in Figure 5.

As it could be seen from Figure 5, the more the size of the population grows, less improvement in the cost is seen due to the fact that the GA results get closer to the global optimum which may not be improved then after. Hence, the effect of population growth beyond 400is more or less subtle.

Expectedly, the execution time increases dramatically as population size is incremented. The variation of execution time versus the population size is presented in Figure 6. Inspecting Figure 5 and Figure 6 simultaneously, it is clear that any increment in population size after the margin of 300 causes slight improvement in operation cost but with tremendous increase in execution time. For instance, shifting from population size of 300 to 900 leads to 0.04% improve in operation cost of the solution with three switching but the execution time of 900 population is approximately 84.4 times longer than that of 300. This poses another factor in selecting the right population size for the algorithm which is the trade-off in cost improvement and the raise in execution time.

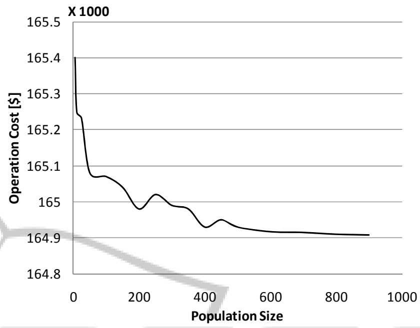

Figure 5: Decrease in cost of operation versus increase in GA's population size setting.

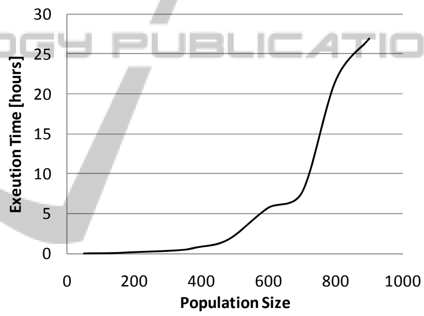

Figure 6: Execution time versus population size.

6.2 Crossover Rate

Figure 7 depicts the variation of the cost of operation of three switching for different values of the GA crossover rate. This empirical analysis justifies the choice of the crossover rate of 80% since the best result is achieved at this point.

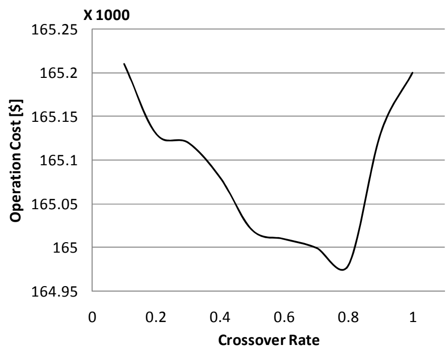

Figure 7: Minimal cost of operation found for 3 switching versus crossover rate.

7 CONCLUSIONS AND FUTURE WORKS

In this work, an optimization model was developed for minimizing the costs of pumping while satisfying fluid flowing and hydraulic constraints. Several major difficulties including complicated electrical tariffs, wear and tear of the pipelines has been implicitly considered. Multi-objective genetic algorithm was chosen as the optimization technique. This technique can help the operators to choose the appropriate operating point based on their experience and unformulated priorities considering both objective functions values. The numerical results indicate the viability and applicability of the model.

As future work directions, we plan to work with our industrial partner, Pembina Pipelines, a Western Canadian oil pipeline operator, to apply our technique to their pipeline networks and to optimize their operational costs. Also, we intend to make use of the flexibility of GA to formulate the multi-products pipelines operation. This problem is challenging due to the fact that the movement of various liquids that are being transported simultaneously by the pipeline should be modelled over the time span.

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LIST OF NOTATIONS

B_j^t Binary variable that indicates the status of the pump on segment *j* at time *t*

CL_j The constant term of the Darcy-Weisbach equation for segment *j*

Con_i Contracted volume of fluid that should be transported in the time frame to the delivery point located on node *i*

$Cost_j^t()$ Operation cost function associated with pump *j* at time *t*

H_i^t Average pressure head associated with node *i* at time *t*

$H_i^{\min}$ Minimum acceptable head of node *i*

H_i^{Max} Maximum acceptable head of node *i*

P_j^t Power consumed by pump *j* at time *t*

PH_j^t Head added to the network by pump *j* at time *t*

PL_j^t Pressure loss of segment *j* at time *t*

Q_j^t Average flow rate associated with pipeline segment *j* at time *t*

Q_j^{Max} Maximum acceptable flow rate of segment *j*

$Q_{i,In}^t$ Summation of the flow entering node *i* at time *t*

$Q_{i,Out}^t$ Summation of the flow exiting node *i* at time *t*

S_j^t Ratio of the speed of the pump on segment *j* at time *t* to its nominal speed

$S_j^{\min}$ Minimum ratio of the speed of the pump on segment *j* to its nominal speed

S_j^{Max} Maximum ratio of the speed of the pump on segment *j* to its nominal speed

SH_i Static head associated with node *i*

V_j^t Valve pressure drop of segment *j* at time *t*

AP_j First coefficient of the head versus flow and speed equation of the pump on segment *j*

BP_j Second coefficient of the head versus flow and speed equation of the pump on segment *j*

CP_j Third coefficient of the head versus flow and speed equation of the pump on segment *j*

a_j First coefficient of the power versus flow and speed equation of the pump on segment *j*

b_j Second coefficient of the power versus flow and speed equation of the pump on segment *j*

c_j Third coefficient of the power versus flow and speed equation of the pump on segment *j*

d_j Fourth coefficient of the power versus flow and speed equation of the pump on segment j

γ The constant term of the power versus flow, efficiency and head equation