

## Multi-objective optimization of transient protection for pipelines with regard to cost and serviceability

S. Mahmood Jazayeri Moghaddas, Hossein M. V. Samani and Ali Haghghi

### ABSTRACT

Transient protection is an important issue in pipeline design. As protective devices impose a huge cost on the project, it is better and more efficient to use optimization models for determination of their position and type with the aim of cost reduction. Except for the cost, the other important issue in obtaining the number and locating of protective devices is the consideration of important operational parameters during the utilization of the pipelines. This paper introduces a new objective function called 'serviceability factor' for achieving the best layout for protection devices by considering five main operational parameters. A double-objective model has been used to optimize the protective devices to obtain the minimum of cost and the most appropriate level of operational parameters. The presented model utilizes the non-dominated sorting genetic algorithm (NSGAI) simultaneously with transient analysis through the method of characteristics. A real pipeline has been optimized using this model and the results are presented in the form of Pareto optimal solutions.

**Key words** | air-chamber, air-inlet valve, optimization, pipeline, serviceability, transient protection

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### INTRODUCTION

Water is one of the main elements in human communities and its transmission from resources to consumers is a very significant topic. A common and reliable method for this purpose is the use of pressurized pipelines. However, the huge implementation cost of such projects, on the one hand, and their technical sensitivities, on the other hand, intensify the necessity for optimal designing with minimum cost and maximum safety and efficiency.

Transient flow due to water hammer is one of the factors considerably affecting the cost and safety of pipelines. In pipelines with pumping stations, this mostly occurs due to sudden pump trip following a power failure.

Transients can introduce large pressure forces and rapid fluid accelerations into the system. These disturbances may result in pump and device failures, system fatigue, or pipe ruptures. Also, transients in pumping systems can lead to water column separation, which can lead to catastrophic

pipeline failures. To prevent undesired effects of these pressures, the use of protective devices is necessary, including air-chambers and air-inlet valves. In pumping pipelines, the air-chamber can appropriately control positive and negative pressures (Stephenson 2002); however, its use imposes a considerable cost on the project. The air-inlet valve can effectively reduce negative pressure consequences (Zhuqing *et al.* 2011) and its price is less than an air-chamber. Thus, for designing a lower cost system, it is better to use air-inlet valves in the pipeline to reduce negative pressure and, consequently, decrease the number and volume of air-chambers; in this way, due to the lower price of air-inlet valves, the total cost of the system would also decrease.

In this circumstance, locating air-chambers and air-inlet valves in appropriate positions could have considerable effects in reduction of the number and sizes of these protective devices and decrease the system protection cost. On the

other hand, apart from the cost, the other important issue in obtaining the number, types, and locating the protective devices, is the consideration of important parameters during the utilization of pipelines.

In the last three decades, numerous studies have been performed on the transients analysis methods in water transmission and distribution systems. Karney & McInnis (1990) analyzed the distribution systems under a wide range of flow conditions, with relatively few restrictions, using modern computer techniques. They presented examples of the dangers of oversimplifying either the physical system or the operating conditions. In another work, McInnis & Karney (1995) addressed the relatively unexplored area of transients in complex pipe networks. They presented a new formulation, permitting system demands to be represented as a distributed pipe flux. Their approach was compared with two conventional methods for modeling demands in pipe networks. Moreover, they compared the results of their model with a field test in a major transmission.

Boulos *et al.* (2005) provided a basic understanding of the physical phenomena and context of transient conditions and presented practical guidelines for their suppression and control; finally, they compared the formulation and computational performance of widely used hydraulic transient simulation schemes.

Some researchers have studied the effects of transient protection devices in pipelines and presented methods for the proper design of these devices. Lee & Leow (1999) studied the effect of air-inlet valve specifications on mitigation of pressurized waves in pipelines due to sudden pump trip and showed that locating air-inlet valves in the higher points of the pipeline could have a more significant effect on controlling negative pressures.

Wang *et al.* (2013) studied the effects of air-chambers in controlling water hammer in pumping systems at high pressures and concluded that in these systems, the key parameter is the volume of the air-chamber.

Stephenson (2002) presented good nomographs for estimation of required volume for the compressed air-chamber as a transient protection design and Zhuqing *et al.* (2011) researched the correct orifice diameter of air-inlet valves.

Many methods have been proposed for the optimization of pipelines and protective devices. Laine & Karney (1997) applied an optimization model for a simple pipeline

connected to a pump and a reservoir. They used a complete enumeration scheme for steady state and transient flow analysis and system design.

Lingireddy *et al.* (2000) developed an optimization method to minimize the cost of compressed air-chambers simultaneously with respect to the pressure constraints. Their study was performed based on a bi-level genetic algorithm (GA) model.

Jung & Karney (2004) studied the effects of transient flow in a selection of optimum diameters in a water supply system with consideration of the design criteria of steady state. They used GA and particle swarm optimization (PSO) for problem-solving and perceived that the combination of GA and PSO in a transient analysis method could considerably improve the efficiency and cost of protection against the transient flow.

Jung & Karney (2006) combined GA and PSO methods for optimization of the size and location of water hammer protection devices in water distribution systems. They minimized maximum pressures, maximized minimum pressures, and minimized minimum and maximum pressure differences. Moreover, they presented several strategies based on surge tank application and pressure regulating valves. However, their study only included the hydraulic performance of protective strategies without consideration of its cost.

Jung *et al.* (2009) formulated the optimum design of a water supply system under transient conditions using a multi-objective optimization algorithm. Their optimization objectives were the minimization of pipeline cost and maximization of hydraulic reliability. In contrast to most optimization models where the demand is considered at the highest possible level, their method assumes demand during system designing as different.

Jung *et al.* (2011) considered a multilevel optimization method for determination of the pipeline sizes in a water supply system as influenced by water hammer. They introduced criteria, called wave damage potential factor, as the first objective function and construction cost of the system as the second objective function. Then, they utilized non-dominated sorting genetic algorithm (NSGA) for optimization of objective functions. In their study, no method or device was used for protection against the transient flow and optimization was only performed on the pipeline size.

Fathi-Moghaddam *et al.* (2013) used a GA method for the optimization of a water penstock tunnel and specification of surge tank for a hydroelectric power plant where the objective function was a benefit to cost ratio. Jung & Karney (2013) optimized the design of a water distribution system for the worst transient condition in two steps. In the first step, a PSO model was used to introduce the critical points with the highest effect on the transient flow. In the second step, a double-objective optimization based on NSGA was performed to determine the optimal sizes of the pipeline to simultaneously minimize the cost and the probability of occurrence of transient flow damage measured through wave damage potential factor.

In the context of the previous studies, the importance of transient effects and the necessity of pipeline protection against them and the application of optimization models for more economical use of transient protection devices is an approved issue. However, what has been neglected is the proper layout of protective devices concerning the utilization and serviceability issues. Devices located in various points of the pipeline might be different regarding serviceability and maintenance, for example, the possibility of quick serviceability. In this regard, since the pipelines pass through suburban areas, other aspects, such as environmental effects and general security of installing devices in each location also should be considered. Thus, in order to perform optimization, it is necessary to consider an objective function that takes into account the serviceability in addition to the cost of water hammer protection devices in pipelines and make a double-objective optimization.

Thus, in this paper, in the optimization of pipeline transient protection devices along with the cost, another objective called ‘serviceability factor’ is proposed and a double-objective optimization is presented. The cost objective is to reach the minimum cost via the proper combination of protective devices, such as different types of air-inlet valves besides the air-chambers. The serviceability factor objective is to achieve the best operation during the project utilization with a selection of the most appropriate layouts for protection devices by considering factors such as: difficulties in servicing during utilization, environmental effects of the use of each device in any location, and general security of installation locations.

The value of the cost objective can be determined by adding the price of devices and their installation cost. However, for calculation of serviceability, various criteria should be considered where some have quantitative, and some have qualitative aspects. Here, the use of multi-attribute decision-making (MADM) could be beneficial for adding together the various mentioned criteria in the form of an objective function, called serviceability factor. On the other hand, since the general aim of this modeling is to protect the pipeline against the pressures due to water hammer, determining the two mentioned objectives should be done with preservation of system pressures at a permissible level. Thus, the presented optimization model should be constrained by the allowable pressures.

To prepare this model, it is necessary to use the double-objective optimization algorithm simultaneously with a method of transient analysis of the pipeline. In this paper, the method of characteristics (MOC) has been utilized for the transient analysis while it is combined with NSGAI optimization algorithm.

In the following, after explaining the MOC transient analysis method, the approach of defining objective functions and the used optimization algorithm are presented, and then the combination of flow analysis and double-objective algorithm is described. Finally, the model is used for a super large-scale real pipeline and the results of optimization are presented in the form of Pareto optimal solutions.

## GENERAL ANALYSIS OF WATER HAMMER

The continuity and momentum equations governing transient flow in pressurized pipelines are as follows (Wylie & Streeter 1993):

$$\frac{\partial H}{\partial t} + \frac{Q}{A} \frac{\partial H}{\partial x} + \frac{a^2}{gA} \frac{\partial Q}{\partial x} + \frac{Q}{A} \sin\theta = 0 \quad (1)$$

$$gA \frac{\partial H}{\partial x} + \frac{\partial Q}{\partial t} + Q \frac{\partial Q}{\partial x} + \frac{fQ|Q|}{2DA^2} = 0 \quad (2)$$

where  $x$  is the distance along the pipe;  $t$  is time,  $H = H(x, t)$  is the total head;  $Q = Q(x, t)$  is the flow discharge;  $D$  is the pipe’s inside diameter,  $A$  is the pipe’s cross-sectional area;  $a$  is the wave speed;  $f$  is

Darcy–Weisbach friction factor and  $g$  is the gravity acceleration. The most common is the MOC. This method is fully described by [Wylie & Streeter \(1993\)](#).

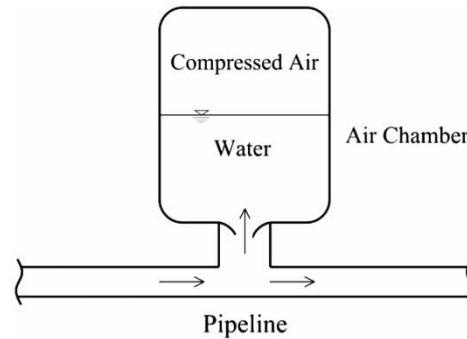
It is worth noting that the analysis of transient fluid was developed based on the following assumptions: (1) the flow is one-dimensional, (2) the fluid is slightly compressible, (3) the pipe walls are linear elastic, and (4) the conduit has expansion joints throughout its length.

The friction factor for unsteady flow is also determined using Brunone formula ([Brunone \*et al.\* 1991](#)).

### PUMP POWER FAILURE, AIR-CHAMBER, AND AIR-INLET VALVE

When a pump trips in a pipeline system because of power failure, the flow discharges and the head decreases at the location immediately downstream of the pump location and a negative pressure wave propagates downstream along the pipe. If the pipe's longitudinal profile is such that the hydraulic grade line intersects with the pipeline, the pressure might be reduced to the liquid vapor pressure which, in turn, might result in a column separation. A positive pressure wave follows the negative wave which results in an increase of the pressure. This issue may cause the pipe to break. If an air-chamber is installed at a location immediately after the pump, during the negative pressure wave, the fluid flows from the chamber toward the pipe to avoid pressure dropping below water vapor pressure; while, during a positive pressure wave, the fluid flows from the pipe towards the chamber resulting in air compression inside the chamber and dropping of pipe pressure in the pipeline. [Figure 1](#) shows a schematic of an air-chamber in a pipeline.

The air-inlet valves considered in this research are combination air-valves in which a large orifice is provided for air inflow and a smaller orifice for the air release. When the combination air-valve is utilized, during a negative pressure wave for which the pressure inside the pipe becomes less than outside, the combination air-valve lets the air enter the pipe and balances the pressure difference. In the next cycle, when the positive pressure wave occurs, the inside pressure becomes higher than outside, the combination air-valve releases inside air to the outside of the pipe. [Figure 2](#) shows a schematic of an air-inlet valve in a pipeline.

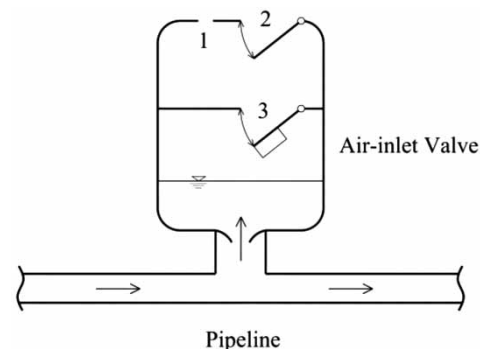


**Figure 1** | Air-chamber in a pipeline.

Boundary conditions of the pump trip are explained in [Wylie & Streeter \(1993\)](#) and equations and details of air-chamber and combination air-valve conditions can be found in [Chaudhry \(2014\)](#). In these references, the boundary conditions are developed based on the following assumptions: (1) for air-chambers it is assumed that the air enclosed at the top of the chamber follows the polytropic relation for a perfect gas; (2) for air-combination valves it is assumed that the airflow into the pipeline is isentropic, the entrapped air remains at the valve location and is not carried away by the flowing liquid, and the expansion or contraction of the entrapped air is isothermal.

### OBJECTIVE FUNCTIONS

The optimization model herein presented considers two objectives: the first objective evaluates the cost of the project and the second objective considers servicing and maintenance during utilization, which is defined as the project



**Figure 2** | Air-inlet valve in a pipeline.

serviceability factor. Since the NSGAI method has been used and this algorithm acts based on the evolution of a population of solutions, it is necessary to calculate the value of objectives for each member of the population. Here, every member is a specific protection plan with some certain protective devices in the specified locations of the pipeline.

**Cost**

The total cost of protective devices in each protection plan constitutes the cost function through the following equation:

$$F = \sum_{i=1}^{N_a} C_{ai} + \sum_{i=1}^{N_v} C_{vi} \tag{3}$$

where  $F$  is the cost function;  $C_{ai}$  is the cost of  $i$ th air-chamber;  $C_{vi}$  is the cost of the  $i$ th air-inlet valve; and  $N_a$  and  $N_v$  are, respectively, the number of air-chambers and air-inlet valves in the pipeline. Since the cost of any device is specified based on its type, it is possible to calculate the  $F$  value having the number and specifications of the devices, for any member of the population.

**Serviceability factor**

In this study, serviceability factor includes parameters that influence utilization after project implementation. Locating protective devices in any point of the pipeline has its special conditions of utilization, serviceability, maintenance, and environmental effects. Thus, serviceability factor should be defined such that it indicates the value of each protection plan based on the above factors. Thus, it is required to identify the effective indexes for these factors in this function. In this study, five indexes have been taken into account, including the distance of devices from a repair and maintenance station, the distance of devices from an access road, the distance of devices from the power source, the environmental effects of installation locations, and general security of the location of devices. Thus, the serviceability factor for each protection plan (each member of the population)

could be defined as follows:

$$G = g(G_1, G_2, G_3, G_4, G_5) \tag{4}$$

where  $G$  is the serviceability factor,  $G_1$  is the index of distance from the service station,  $G_2$  is the index of distance from the road,  $G_3$  is the index of distance from the power source,  $G_4$  is the environmental factor, and  $G_5$  is the general security factor. In this paper, the environmental factor is an indicator that reflects the impact of pollution caused by repair and maintenance of protection devices installed along the pipeline. Also, the general security factor refers to the level of deliberate sabotage risk that threatens the pipeline.

Since any protection plan can include some devices, each of the mentioned indexes from  $G_1$  to  $G_5$  could be calculated from the following equation:

$$G_j = \frac{\sum_i^{NumDevice} G_{ij}}{NumDevice} \text{ for } j = 1, 2, 3, 4, 5 \tag{5}$$

where  $G_j$  is the average amount of  $j$ th serviceability index in a protection plan.

To calculate the  $G$  value in each protection plan, it is necessary to summarize the effect of  $G_1$  to  $G_5$  indexes in an objective function. To this end, MADM concepts are used to apply the effect of five indexes in  $G$  function according to their amount of significance. The considered MADM model is formulated in the form of **D** decision-making matrix as follows:

		index				
	plan	$G_1$	$G_2$	$G_3$	$G_4$	$G_5$
$D =$	$A_1$	$r_{11}$	$r_{12}$	$r_{13}$	$r_{14}$	$r_{15}$
	$A_2$	$r_{21}$	$r_{22}$	$r_{23}$	$r_{24}$	$r_{25}$
	$A_3$	$r_{31}$	$r_{32}$	$r_{33}$	$r_{34}$	$r_{35}$
	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
	$A_m$	$r_{m1}$	$r_{m2}$	$r_{m3}$	$r_{m4}$	$r_{m5}$

(6)

where  $A_1$  to  $A_m$  are pipeline protection plans (members of optimization population), each one with specified numbers, types, and locations of protective devices, and  $r$  is the value of each index in any protective plan.

Of the five mentioned indexes,  $G_1$  to  $G_3$  are quantitative and measured through distance (unit of km),  $G_4$  and

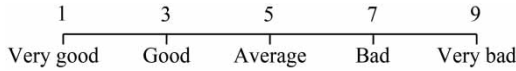


Figure 3 | Qualitative spectrum with bipolar scale.

$G_5$  are qualitative and a qualitative spectrum (from very good to very bad) has been used for their determination. Thus, to determine function  $G$  from the five indexes, it is necessary first to change all indexes to quantitative values. To this end, the measurement of qualitative indexes was performed with bipolar scale as shown in Figure 3.

Based on this scale, the best possible value can be measured for the index from 1 to 9. The value 5 is the break-point between desired and undesired condition.

After quantification of all indexes, parameter  $D$  with quantitative values is formed. Now, due to the heterogeneity of measurement scales, it is necessary to make the values dimensionless. In this study, fuzzy descalization was used (Zeleny 1982). Accordingly, each  $r_{ij}$  is transformed into dimensionless value  $n_{ij}$  using Equation (7):

$$n_{ij} = \frac{r_{ij} - r_j^{min}}{r_j^{max} - r_j^{min}} \tag{7}$$

where  $r_j^{max}$  and  $r_j^{min}$  are, respectively, the maximum and minimum possible values for  $j$ th indexes.

Now, the dimensionless  $D_n$  decision-making matrix is formed as follows:

		index				
	plan	$G_1$	$G_2$	$G_3$	$G_4$	$G_5$
$D_n =$	$A_1$	$n_{11}$	$n_{12}$	$n_{13}$	$n_{14}$	$n_{15}$
	$A_2$	$n_{21}$	$n_{22}$	$n_{23}$	$n_{24}$	$n_{25}$
	$A_3$	$n_{31}$	$n_{32}$	$n_{33}$	$n_{34}$	$n_{35}$
	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
	$A_m$	$n_{m1}$	$n_{m2}$	$n_{m3}$	$n_{m4}$	$n_{m5}$

(8)

The next stage for determination of  $G$  values in each protection plan is to determine the weights for indexes to obtain the effect of each index in the value of the  $G$  function for each protection plan. Here, the weights of indexes on each other are assumed stable and consistent; thus, for their determination, it is possible to use mutual judgments. This means those indexes are weighted based on an

appropriate judgment on each other in pairs and the following matrix is constructed:

$$W = \begin{matrix} & G_1 & G_2 & G_3 & G_4 & G_5 & \frac{w_1}{w_1} & \frac{w_1}{w_2} & \frac{w_1}{w_3} & \frac{w_1}{w_4} & \frac{w_1}{w_5} \\ G_1 & a_{11} & a_{12} & a_{13} & a_{14} & a_{15} & \frac{w_2}{w_2} & \frac{w_2}{w_2} & \frac{w_2}{w_3} & \frac{w_2}{w_4} & \frac{w_2}{w_5} \\ G_2 & a_{21} & a_{22} & a_{23} & a_{24} & a_{25} & \frac{w_3}{w_3} & \frac{w_3}{w_3} & \frac{w_3}{w_3} & \frac{w_3}{w_4} & \frac{w_3}{w_5} \\ G_3 & a_{31} & a_{32} & a_{33} & a_{34} & a_{35} & \frac{w_4}{w_4} & \frac{w_4}{w_4} & \frac{w_4}{w_4} & \frac{w_4}{w_4} & \frac{w_4}{w_5} \\ G_4 & a_{41} & a_{42} & a_{43} & a_{44} & a_{45} & \frac{w_5}{w_5} & \frac{w_5}{w_5} & \frac{w_5}{w_5} & \frac{w_5}{w_5} & \frac{w_5}{w_5} \\ G_5 & a_{51} & a_{52} & a_{53} & a_{54} & a_{55} & \frac{w_5}{w_1} & \frac{w_5}{w_2} & \frac{w_5}{w_3} & \frac{w_5}{w_4} & \frac{w_5}{w_5} \end{matrix} \tag{9}$$

where  $W$  is the weights matrix and  $a_{ij}$  is the weight of index  $i$  with respect to index  $j$  ( $a_{ij} = w_i/w_j$ ); moreover:

$$a_{ik} \cdot a_{kj} = a_{ij}, \quad a_{11} = a_{22} = a_{33} = a_{44} = a_{55} = 1 \tag{10}$$

To determine each array of matrix  $W$ , it is sufficient to determine the significance of each index with respect to other indexes with empirical judgment. For example, if the significance of index 1 is two times more than index 2,  $a_{12}$  will be equal to 2 and  $a_{21}$  is equal to 0.5.

Now, it is possible to calculate the weight of each index through normalization of each  $j$  column of matrix  $W$ , i.e.:

$$W_j = \frac{a_{ij}}{\sum_{k=1}^5 a_{kj}} \text{ for } j = 1, 2, 3, 4, 5 \tag{11}$$

At the end, the value of function  $G$  for every protection plan, in other words, for every member of the solution population, can be calculated through the following equation:

$$G = W_1G_1 + W_2G_2 + W_3G_3 + W_4G_4 + W_5G_5 \tag{12}$$

### CONSTRAINTS HANDLING

In every protection plan, it is necessary to make the pressures on all points within allowable limits. In this study, the pressure constraints are added to each objective function in the form of a penalty function. Concerning minimization of the optimization model, this function is defined



as follows:

$$PF = M \sum_{j=1}^{N_j} \max\left(0, \left(P_{min.all}^j - P_{min}^j\right)\right) + M \sum_{j=1}^{N_j} \max\left(0, \left(P_{max}^j - P_{max.all}^j\right)\right) \quad (13)$$

where  $M$  is the penalty factor,  $N_j$  is the number of computational nodes of the pipeline,  $P_{min}^j$  and  $P_{max}^j$  are, respectively, the minimum and maximum pressures at node  $j$ ,  $P_{min.all}^j$  is the minimum allowable pressure at node  $j$ , i.e., a safe pressure value far enough from the water vapor pressure at that node, and  $P_{max.all}^j$  is the maximum allowable pressure at node  $j$ , which is determined according to the wall thickness of the pipe. Equation (13) indicates that  $PF$  should be zero when all nodal pressures are in the allowable ranges and it equals a positive large number when they are violated. The penalty factor  $M$  is an arbitrary positive number determined by trial and error to achieve the best performance of GA in terms of both constraint handling and searching for the global optima in the feasible decision space. Using the penalty function causes that performance impact of protection devices to be tested in the model. Smaller values of  $PF$  indicate better capability of devices (air-chambers and air-valves).

Thus, objective functions are shown in the form of  $F_1$  and  $F_2$  in their final form for optimization:

$$F_1 = F + PF \quad (14)$$

$$F_2 = G + PF \quad (15)$$

## OPTIMIZATION MODEL

In this study, two objectives are followed to determine the best combination of protective devices and their localization in the pipeline. This optimization is double-objective with the following general form:

$$\text{minimize } H(X) = \{F_1(X), F_2(X)\}$$

$$X = (x_1, x_2, \dots, x_n) \quad (16)$$

where  $H$  is the objective space,  $F_1$  and  $F_2$  are objective functions, and  $X$  is decision-making vector including all decision variables.

Since the main issue of optimization is minimization, the functions must be such that their minimization is on the desired side.  $F_1$  is related to the cost, and its minimization is desired. Also the minimum amount of  $F_2$ , that depends on serviceability indices, is appropriate (based on what was previously mentioned; the reduction of  $G_1$  to  $G_5$  is desired and improves the serviceability of the system). Thus, the reduction of serviceability factor and  $F_2$  is favorable.

Unlike one-objective optimization, multi-objective problems yield a collection of solutions rather than a certain solution such that each solution from this set could be an optimum. Multi-objective optimization methods can be divided into three general categories: evaluating methods, non-Pareto methods, and Pareto methods. Among these, Pareto methods are more flexible and stronger for engineering problems since they can obtain optimum multi-purpose solutions of Pareto in one implementation. In this paper, NSGAI (Deb et al. 2002) has been used, and is an evolutionary elitist algorithm through the Pareto method and based on GA.

Decision variables in objective functions are cost and serviceability indexes that are dependent on the location of air-chambers and their volume, the location of air-inlet valves and the diameter of their orifice. In this study, to define the permissible space of decision variables, first some locations are chosen to place each protection device and for the specification of each protection device, certain predetermined selections are considered according to a list. The location and type of the protection devices can vary in this way in the defined space. To determine objective functions, the price of each device is included in its specification list and for each candidate place, the distance from the service station, access road and power station, the environmental index, and the general security index are defined beforehand.

Accordingly, the optimization algorithm includes the following steps:

1. The same as the GA method, an initial population of decision-making variables are randomly produced in the permissible space. Each member of this population includes a set of decision variables that are called chromosomes.

2. With defined specifications for each chromosome, hydraulic analysis of water hammer is performed in the pipeline due to the predetermined scenario for pump power failure and the objective target values for each chromosome is obtained using its results. It is such, that concerning the protective devices in each member of the population, the total cost is computed and five indexes constituting serviceability factor also obtained. Then, using Equations (4)–(15),  $F_1$  and  $F_2$  values for each chromosome are calculated.
3. The population is sorted based on non-dominated sorting according to the values of functions allocated to chromosomes, such that the members in the first front are a fully non-dominated set by all other members of the population. The members of the second front are dominated just by the members of the first front, and this trend continues in this way on other fronts so that all members in each front will get a rank based on the number of the category (according to Figure 4). This sorting is the basis for non-dominated sorting.
4. Crowding distance controlling parameter for any member of each front can be calculated through objective functions from the following equation:

$$d_j(k) = \sum_{i=1}^2 \frac{F_i(k-1) - F_i(k+1)}{F_i^{max} - F_i^{min}} \quad (17)$$

where  $k$  is the number of members,  $d_j(k)$  is crowding distance,  $k-1$  and  $k+1$  are the number of members beside the intended member in the related front,  $F_i$  is  $i$ th objective function and  $F_i^{min}$  and  $F_i^{max}$  are, respectively, the minimum and maximum values of  $i$ th function in the intended front. Crowding distance indicates the closeness

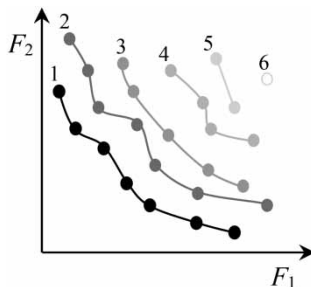


Figure 4 | Non-dominated sorting.

- of the member to other members of the population in each front. Now, the population members are sorted first based on the front number and the second based on the crowding distance criterion such that the member with a lesser front number is in a higher rank and the member with higher  $d_j$  value is in a higher rank if some of the members have the same fronts.
5. A new generation of chromosomes is produced using the parent selection method through the binary tournament method (Haupt 2004) and application of crossover through BLX-a (Eshelman & Shaffer 1993), and they replace bad chromosomes in the population.
6. A few genes except genes of the best chromosomes that are in the first front are randomly mutated.
7. Convergence criterion is controlled. If GA chromosomes are sufficiently similar, optimization is stopped; otherwise, this algorithm returns to step 2 to iterate with a new population.

At the end of the model, optimum Pareto solutions that are members of the first category in the solution population are obtained (according to Figure 5).

Using the obtained solutions and based on the engineering judgments, it is possible to select the appropriate answer to preserve the values of objective functions in the desired level from the Pareto front.

## CASE STUDY

The presented optimization model was used for a super large-scale real pipeline project with a discharge of  $8.5 \text{ m}^3/\text{s}$ , called the ‘Qadir project’, in the southwest of

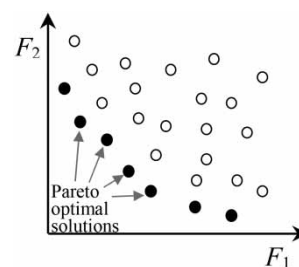
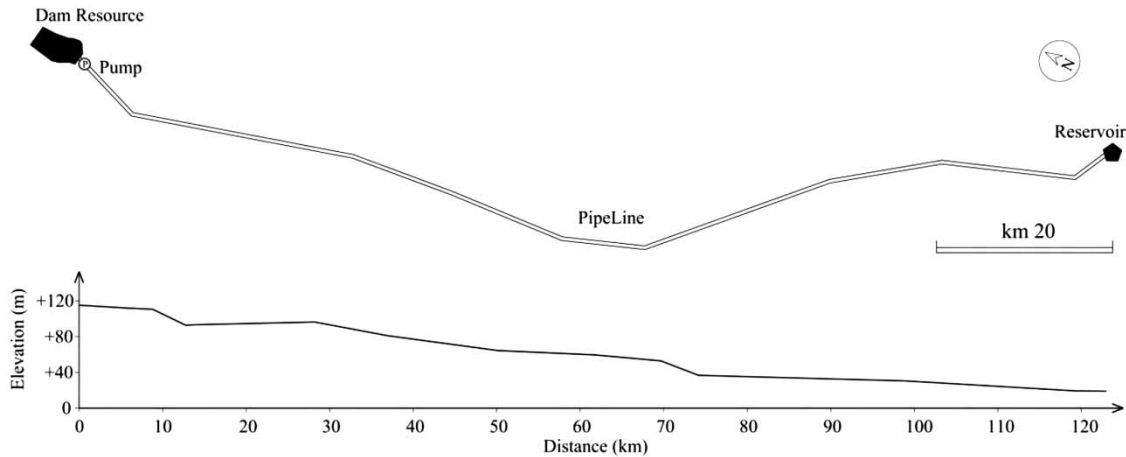


Figure 5 | Pareto optimal solutions.





**Figure 6** | The longitudinal profile and plan of the Qadir pipeline.

Iran and the results are presented in this section. The pipeline, with a length of 127 km and a diameter of 2,250 mm, transfers water from the Karkheh dam reservoir to Ahvaz city. The plan and profile of the pipeline are presented in Figure 6 and the specification of the pipes and pumping station are shown in Table 1.

In Table 1, the maximum allowable pressure is considered with respect to pipe wall thickness and the minimum allowable is selected as water vapor pressure for cavitation prevention. The upstream end of the pipeline is located at the height of 115.6 m and its downstream at the height of 22.3 m of sea level. This pipeline passes through desert and agricultural areas parallel to the Kahrkeh River and there is no accessible asphalt road along its path. Two servicing and maintenance stations are located at the beginning and end of the pipeline. Accessibility to the power source is also limited. Security in agricultural areas is good, but in the desert area it is not

appropriate. Since the pipe approaches the river at some points, the maintenance and servicing of protection devices of water hammer in some areas could create environmental problems. To perform water hammer analysis and predict the positions for locating protective equipment, the pipeline has been divided into 64 sections concerning ground profile, such that, first the pipe connections are at the slope change points, and second, the pipe lengths do not exceed 2,000 m for better protection of the pipeline in the uniform slope. Table 2 presents the lengths of 64 pipes constituting the pipeline and Figure 7 shows this division in system plan. The connection points of these sections for locating equipment such as air-chambers or air-inlet valves is predicted. Moreover, in Figure 7, the situation of the access road, the power station and service centers, the relative status of the environmental index, and general security of all connection points of pipe are shown.

**Table 1** | The specification of pipes and pumping station of the Qadir project

Pipeline properties		Pump station properties	
Pipe diameter	2,250 mm	Pump type	Horizontal centrifuge
Max allowable pressure	37 bar	Number of pumps	10
Material	Steel	Total head	160 m
Min allowable pressure (water vapor pressure)	0.13 bar	Total discharge	8.5 m <sup>3</sup> /s
Thickness	19 mm	Rotational speed of each pump	1,760 rpm
Wave speed	1,000 m/s	Outlet diameter	520 mm

Table 2 | Length of pipes in system

Pipe #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Length (m)	150	2,000.09	2,000.08	2,000.01	2,808.93	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,850	2,000.01
Pipe #	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Length (m)	2,000.01	2,000.02	1,213.67	2,000.01	2,000	2,000	2,000.05	2,000.05	1,696.86	2,000.07	1,999.87	2,000.21	2,000	2,000	2,000
Pipe #	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45
Length (m)	2,083.88	2,000.03	2,000.02	2,000.03	2,000.02	1,317.12	2,000.05	2,000	2,000	2,000.04	2,000	2,000.05	2,000	2,000	2,000
Pipe #	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60
Length (m)	2,000	2,072.78	2,000	2,000	2,000	2,000	2,000	2,819.41	2,000	2,000	2,000	2,000	2,000	2,000	2,000
Pipe #	61	62	63	64											
Length (m)	2,015.33	2,000	2,000	2,244.13											

According to the explained model, for optimization of transient protection devices against pump station power failure in this pipeline, all connection points of pipes have been considered as candidate points for locating protective devices. Seven types of air-chamber with different volumes and three types of air-inlet valves with different orifices were considered as possible selections for candidate points. Table 3 shows the list of protective device specifications that are usable in this optimization along with the cost of each one. The optimization model selects decision variables for each candidate point from these two lists. Although in the model there is the possibility of a lack of protective device for each candidate point, it is the state that nothing is selected from the options presented in a candidate point.

To determine the weights of serviceability indexes, it is necessary to form a relative weight matrix with engineering judgment. This matrix is formed for this issue based on the regional condition and the facilities for servicing and maintenance according to Table 4.

Using *W* matrix and Equation (10), for each column of *W* matrix, the weight of each index is calculated as follows:

$$W_1 = 0.25, W_2 = 0.125, W_3 = 0.125, W_4 = 0.166, W_5 = 0.334$$

The population is considered to be 200 and the mutation rate is assumed to be 0.02. A maximum number of permissible generations for implementation are also set as 1,000.

## RESULTS

In various implementations, the model reaches convergence after about 600 generations. The result of this optimization is shown in Figure 8 in the form of Pareto optimal solutions.

In Table 5, the specification and location of protection devices related to some Pareto solutions that are shown in Figure 8 are presented.

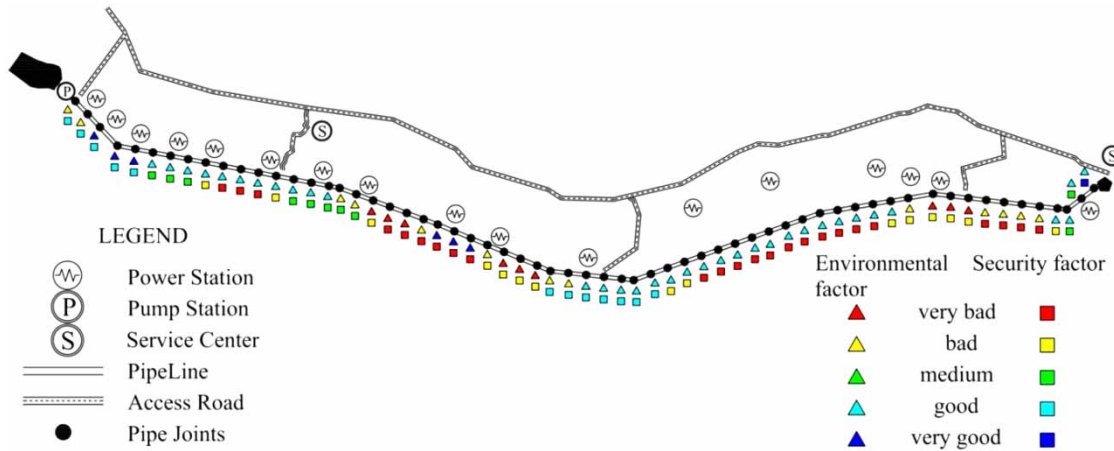


Figure 7 | The division of the pipeline and the status of serviceability indexes in the pipeline.

Any row in Table 5 indicates the specification of protective devices for one of the Pareto solutions obtained in the problem. The position and type of air-inlet valve and air-chambers of any solution are specified in the related rows, and cost function and serviceability are also shown. In this table, any device is specified by a number and a letter in parentheses; the number indicates the number of

Table 3 | The specification of protective devices used in optimization model

Air-inlet valve			Air-chamber		
Type	Orifice diameter Diameter (mm)	Cost (\$)	Type	Volume (m <sup>3</sup> )	Cost (\$)
A	300	7,000	A	10	55,000
B	450	9,000	B	20	100,000
C	600	12,000	C	25	250,000
			D	30	300,000
			E	35	340,000
			F	40	367,000
			G	60	530,000

Table 4 | The weight matrix of the Qadir project problem

	1	2	2	1.5	0.75
	0.5	1	1	0.75	0.375
W =	0.5	1	1	0.75	0.375
	0.67	1.33	1.33	1	0.5
	1.33	2.67	2.67	2	1

the pipe next to the device and the letter indicates device type. To compare the manner of optimum protection solutions shown in Table 5, the graphs of minimum pressures in the pipeline related to two solutions and the plan without protection devices are shown in Figure 9. According to this figure, mentioned solutions that contain protection devices protect the system as desired, and despite the difference in the cost and serviceability and pressures in all points, these solutions are higher than minimum permissible pressure and the hydraulic constraints are satisfied. This condition is also established for maximum allowable pressures in all of the solutions.

Concerning the obtained Pareto front in the optimization of this issue, there is the possibility of selecting a diverse range of protection plans with consideration of technical and economic criteria and considering utilization parameters.

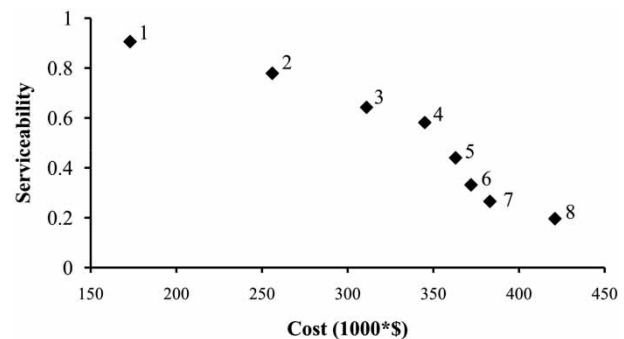
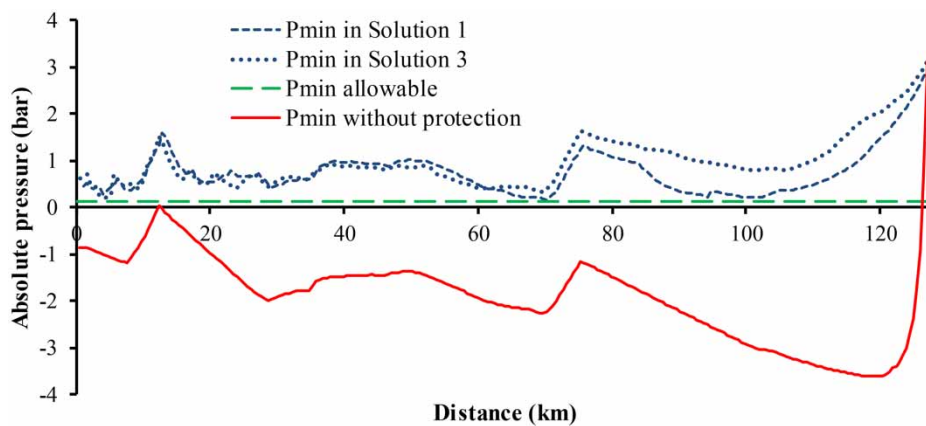


Figure 8 | The optimum Pareto solutions for the Qadir project.

**Table 5** | The specification of some of the protection plans present in Pareto solutions

Solution#	Air-inlet valves (location and type)	Air-chambers (location and type)	F <sub>1</sub> cost (1,000*\$)	F <sub>2</sub> (serviceability factor)
1	4(A),8(A),10(A),15(A),33(A),47(A),51(A),56(A),61(A)	27(A), 49(A)	173	0.906
3	4(A),10(A),15(A),29(A),33(A),47(A),56(A),61(A)	2(B), 27(A),49(B)	311	0.642
4	4(A),14(A),33(A),50(A),56(A)	2(B),8(A),27(B),49(A)	345	0.582
7	4(A),10(A),14(A),56(A)	2(B),27(B),32(A),49(B)	383	0.265
8	4(A),14(A),56(A)	2(B),27(B),32(B),49(B)	421	0.196

**Figure 9** | Minimum pressure along the pipeline.

## CONCLUSION

In this study, an optimization model is presented to obtain the optimum specification of the pipeline protection plan against water hammer due to pump power failure. Here, the determination of the locations and specification of air-chambers and air-inlet valves in the pipeline have been considered. The presented model provides designers with a collection of Pareto optimal solutions for decision-making with consideration of two objectives. The first objective is cost and the second objective, that is presented for the first time in this study, is the serviceability factor which is obtained by a combination of five effective indexes on system servicing and maintenance using MADM. In the mentioned optimization model, NSGAI was used as a multi-objective optimization method combined with transient flow analysis through the MOC method. This model has been used in a real large project in the southwest of Iran. The results of this case study show that the use of serviceability objective along with cost can provide a broad range of

solutions and help designers in the selection of the proper specification of protection systems against water hammer with simultaneous consideration of cost and utilization issues. The other advantage of the presented model is pipeline hydraulic constraint handling using the penalty functions in objectives. This approach means that all solutions are achieved with the certainty of pressure justifiability.

However, given that the model is based on GA and MOC transient analysis, its main weakness is that it is very time-consuming. This issue creates significant restrictions for the optimization of long pipelines. Applying transient analysis in the frequency domain instead of time domain, and using faster optimization models, can be useful to improve the model convergence.

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First received 1 March 2016; accepted in revised form 26 February 2017. Available online 20 June 2017