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Optimization of pipeline lifecycle cost using alternatives with different life spans

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ABSTRACT

This paper suggests a pipeline project optimization approach that compares alternatives with different life spans. The average inflation rate is used to project the future maintenance, operation and replacement costs. The average interest rate is used to express all the costs in Equivalent Real Annual Cost (ERAC), which is the correct cost form to compare alternatives with different life spans. The pipe diameter, material, pressure rating, surge tank size, and inlet/outlet resistances are the decision variables. A software was compiled with a commercial pipeline software to generate all the possible design alternatives based on the decision variables. Pipe initial cost as well as operation and maintenance costs are computed for each design alternative. The alternative with the least ERAC value is the optimum one. It was found that the approach can lead to substantial savings in pipeline projects cost. For pipes 800 mm in diameter or larger, and when selecting the optimum diameter, savings are between 23 and 27% in the total project cost. When imposing certain pipe material savings in overall cost will be 8.5, 16.3 and 31.3% for ductile iron, GRP and mild steel pipe material, respectively.

Key words: cost, life spans, optimization, pipeline

HIGHLIGHTS

- Applying the proposed approach to pipeline projects may result in significant savings without sacrificing quality.
- Such an approach can offer a very clear and objective choice, free of personal bias toward any one alternative (e.g., pipe material).
- Considering hydraulically equivalent alternatives and using the correct tool to recognize the changing value of money will facilitate unbiased comparisons of costs.

1. INTRODUCTION

Pipeline design is typically accomplished for steady-state flow conditions, with water hammer protection devices representing a small portion of the overall pipeline cost. However, this approach has proven to be inaccurate (Jung & Karney 2006). A few studies have addressed the optimization of pipe networks for steady-state and transient flow conditions based on pipe size only, that is, without the use of water hammer protection devices (Djebedjian *et al.* 2005; Afshar 2006). Several studies have addressed the optimization of surge protection devices. For example, for high points along a pipeline, safe surge protection can be provided using a simply designed pressure vessel. In certain circumstances, the resulting vessel can be very large and expensive. It may be possible to design surge protection using a combination of a smaller pressure vessel and special air valves (Matringe 2004). An air inlet valve combined with a double-acting air valve of low air discharge capacity can replace a surge tank connected to the apex point of a pipe (Espert *et al.* 2008). Genetic algorithms (GAs) and particle swarm optimization (PSO) have been used to optimize the use of surge protection devices with respect to their number, sizes, and locations (Jung & Karney 2006). Six different scenarios for using a predetermined number of devices (e.g., two surge tanks, one surge tank, and one pressure-relief valve, or three pressure-relief valves) have been considered, and GAs and PSO techniques have been used to find the optimal sizes and locations of the devices.

Pipe network optimization under transient flow conditions has been examined (Laine & Karney 1997; Lingireddy *et al.* 2000; Jung *et al.* 2007, 2011; Moneim *et al.* 2010; Mansouri *et al.* 2015; Saminu *et al.* 2015). Laine & Karney (1997) applied optimization to a simple pipeline system consisting of a pipe connecting a pump to a storage tank. A complete enumeration procedure combined with a probabilistic selection procedure was incorporated into steady-state and transient-state flow analyses. Lingireddy *et al.* (2000) demonstrated that a specific surge tank design model can produce an optimal set of decision variables while meeting a predetermined pressure constraint. Boulos *et al.* (2005) presented a detailed flowchart for unsteady flow analysis. The chart aids in the selection of components for pressure surge control and suppression in pipelines and water distribution systems (WDSs). They suggested that transient analysis should be performed to assess the impact of each proposed strategy on network performance and operation. Jung *et al.* (2007) showed that it is important to carry out systematic transient analysis to resolve complex transient characterizations and to adequately protect a WDS. Jung *et al.* (2011) demonstrated the effect of the interaction of steady and transient levels on the selection of component size for pressure surge protection.

2. METHODOLOGY

A GA-based optimization technique was developed for the optimal design of long water supply pipelines, including optimal surge protection based on surge tanks. The objective function to be minimized is the ERAC of the pipeline, pumps, surge tank and pipe maintenance and pump operational energy over the predetermined service life of each project component. The primary constraints for the optimization problem involve pipe velocities and nodal pressures. The user may specify upper and lower bounds on the pipe velocities and nodal pressures. Constraint violations are handled through penalty functions so that the optimization technique will always produce an optimal solution even when a few pressure and velocity constraints are violated, using appropriate information provided on the magnitude of each violation in terms of the penalty cost.

In general, the surge tank is the most expensive of the various types of surge protection methods. The proposed optimization technique was aimed at optimizing the sizing of a surge tank for a given pipeline system. The primary variables that control the overall size of a surge tank are the initial gas volume and connection resistances (inflow and outflow).

While the size of a surge tank depends on several factors associated with the transmission main, the steady-state velocity in the pipeline can have the most significant influence on the overall size of the surge tank. The steady-state velocity depends on the size (diameter) of the pipeline. When the size of the pipeline changes, another pressure rating may be selected to satisfy the appropriate pressure constraints. In addition, pipes of different materials may have different costs and, more importantly, different associated celerity (wave speed) values. Therefore, it is prudent to include pipe diameter, material, and pressure rating in the decision variable set.

The optimization procedure, which is implemented in a specially designed software program, includes five decision variables: two decision variables associated with the surge tank (the initial gas volume and connection resistance) and three decision variables associated with the pipeline (diameter, material, and pressure rating). The first two decision variables can be any real number (decimal values), while the remaining three can only be specific values selected from a list of suitable and available pipe data. After legitimate optimal solutions are obtained from the GA software, further analysis is performed to consider the pump's initial costs, the pump's future operational costs, and future pipe maintenance costs for the pipe over a predetermined service life, which is expressed as the ERAC.

Pipe data (D, M, and T) should be selected from the specified rank-ordered pipe characteristics table. Steady-state hydraulic constraints are through an external steady-state hydraulics program. Transient hydraulic constraints are handled through an external surge analysis program.

Once a vector of optimal solutions is obtained using GA (i.e., optimal with respect pipe material, diameter and surge tank), further optimization is performed by adding the operational and maintenance costs of the project over the predetermined service life for each pipe material. The overall total cost for each solution is obtained in terms of the ERAC, and the solutions are arranged from best fit to least fit based on their ERAC values.

2.1. Transient event

Pump trip is a transient event that cannot be avoided in the real world and may result from pump failure or power outage. For this reason, the hydraulic analysis in this study includes simulating a pump trip by fully closing a valve just downstream of the pump in 2 s. This event is considered for each solution suggested by the GA in search for the best fit design. This event causes extreme low and high pressures, which may exceed constraints for some design alternatives, and so, there is a need to apply a penalty to their costs, to ensure that these alternatives are among the least fits.

2.2. Cost evaluation

In this study, the initial pipe cost included the material, transportation, and installation costs. All project costs (initial, maintenance, and operational) were first converted to net present values (NPVs). Comparing the NPVs of the alternatives with unequal service lives and in the presence of inflation would be inaccurate. As stated previously, the correct approach to handle alternatives with different lifespans in the presence of inflation is to convert the cost from NPVs to ERAC.

2.3. Interest and inflation rates

Since the pipe service life is very long and interest rate and inflation cannot be predicted during such a long time, they will be taken as constant values based on the available historical data. In the following cost analysis, the average historical values of the interest and inflation rates are considered as 3.7% and 2.8%, respectively.

2.4. Service lives of pipes and pumps

To evaluate the total cost, it is necessary to consider a reasonable service life for each project component. The average service life for ductile iron pipes (DICL) pipes under harsh ground conditions and early laying practices is 55.8 years, and the corresponding value for benign ground conditions and evolved laying practices is 109.6 years. For mild steel cement-lined (MSCL) pipes, the expected service life is 86.3 years (AWWA 2012). The relevant value for glass fiber reinforced plastic (GRP) pipes is 60 years. Since the pipeline considered in the case study is installed under dry and benign soil conditions, 110, 86, and 60 years were considered as the expected service lives of the DICL, MSCL, and GRP pipe materials, respectively. The service life for pumps was assumed to be 25 years. This means that after every 25 years, the cost of a new set of pumps is added to the overall cost in the cost analysis. All the costs are considered as NPVs considering the inflation and discount rate. Then, they are converted to ERAC to allow a proper comparison among the solution alternatives.

2.5. Initial, operational, and maintenance costs

The objective of cost estimation is to facilitate investment decisions. To compare projects with different service lives, one could use the replacement chain approach, which entails calculating the total NPV over the lifecycle for each alternative. However, the total cycle for this case study would be as long as $40 \times 86 \times 110$ years. Thus, this approach requires very high computational effort. A simpler approach, which yields identical results to the replacement chain method, is called equivalent annual cost (EAC). It is the annual cost of owning, operating, and maintaining an asset over its entire life. It allows a comparison of the cost effectiveness of various assets with unequal lifespans. One could think of it as the annual cost of the project if it were to be paid as an installment at the end of each year over the whole project service life.

In the presence of inflation, the analyst should consider rising prices due to inflation when calculating the NPV over the lifecycle using the replacement chain approach. For instance, consider that the GRP pipe project needs to be replaced after 60 years. One can use the NPV for the first period of the project and apply inflation to it to obtain the NPV for the second period (i.e., $NPV_2 = NPV_1(1+ \text{inflation})^{60}$) and so on for the following periods. Fortunately, the EAC approach can be modified to provide results identical to those of the replacement chain method (in the presence of inflation), namely, ERAC.

Using ERAC instead of EAC enables one to account for inflation. Thus, any NPV can be converted into the *ERAC* using the following equation:

$$ERAC = \frac{NPV}{A_f} \tag{1}$$

where *NPV* is the net present value of the total cost or any present value of any cost (maintenance, operational, or capital), and A_f is the present value annuity factor for real rate r and economic life n, which is given by

$$A_f = \frac{1}{r}\left(1 - \frac{1}{(1+r)^n}\right) \tag{2}$$

Here, n is the project life length (e.g., years) and r is the real rate, which is given by

$$r = \frac{d+1}{f+1} - 1 \tag{3}$$

where f denotes the average inflation rate expected during the lifetime of the pipeline project, and d refers to the average interest (discount) rate expected during the lifetime of the project.

The project with the lower ERAC is a better investment. Total costs and other aspects of costs can thus be compared in the same manner. The ERAC approach is much simpler than the replacement chain approach, and thus, is used in this case study.

The cost components for the project and the manner of their computation are described below.

2.5.1. Initial cost of the pipe, surge tank, and pump

This cost component includes the initial price of the pipe, as well as its transportation, excavation, and installation costs. This cost is already expressed in terms of NPV. A survey was conducted to obtain the initial cost of the pump. According to this survey, the average initial pump price is US $250/kWh input energy. The input energy is computed by dividing the output energy by the assumed pump efficiency (80%). The initial cost of the first pump is already expressed in terms of NPV. It should be converted to ERAC. When the service life of the pump set is over, a replacement set is to be installed, and its cost is to be expressed in ERAC. The cost of the surge tank is estimated using the average cost per cubic meter obtained from actual surveys. Thus, the initial cost of the pipe, surge tank, and pump in ERAC is given by

$$C_{IC} = \frac{1}{A_f}\left(C_{PI} + C_{ST} + \sum_{k=0}^{NPS-1}\frac{(C_{PU1})(1+f)^{l\times k}}{(1+d)^{l\times k}}\right) \tag{4}$$

where C_{IC} refers to the total initial cost of the pipe, protection surge tank, and pump in ERAC, C_{PI} is the initial cost of the pipe, C_{ST} refers to the initial cost of the surge tank, and k denotes the number of pump sets to be installed during the project service life (including the first pump set). *NPS* refers to the number of pump sets expected to be installed during the lifetime of the pipe, C_{PU1} denotes the cost of the first pump set (already expressed in terms of NPV), and l denotes the assumed lifetime of the pump set in years. Multiplying the current pump set price C_{PU1} by $(1+f)^{l\times k}$ applies the effect of inflation. Thus, one would obtain the cost in a future year. Dividing the resulting number by $(1+d)^{l\times k}$ converts the number to the NPV. Dividing the result by A_f gives the corresponding ERAC for the cost.

2.5.2. Pump energy cost

Pump energy cost is estimated using the current energy cost per kWh. It is necessary to apply inflation to the current energy cost to estimate the energy cost for each year of the project service life. The resulting total energy cost is expressed in terms of NPV using the interest rate and is then converted to the ERAC. The following equation shows how inflation and interest rates are utilized to estimate the ERAC of pump energy:

$$C_{Wp} = \frac{1}{A_f}\left(\sum_{i=1}^{n}\frac{(C_{Wp0})(1+f)^{i}}{(1+d)^{i}}\right) \tag{5}$$

where C_{Wp} denotes the pump energy cost as the ERAC, C_{Wp0} denotes the pump energy cost just before the start of the project (in this case, $C_{WP0} =$ US$0.0408/kWh, already in terms of NPV), i denotes the year for which the energy cost is computed, n refers to the length of the project life, and f and d are as defined earlier. Again, applying inflation is mandatory because the prices rise each year. Dividing the result by $(1+d)^i$ converts the cost to the NPV, and dividing it by A_f, converts the NPV of the total energy cost throughout the service life of the project into the ERAC.

2.5.3. Pipe maintenance cost

The pipe maintenance cost includes all the expected repair costs, including replacing short segments of pipes (6 m or 12 m in length). It is calculated using the following equation:

$$C_M = \frac{1}{A_f}\left(\sum_{i=1}^{n}\frac{(h_i)(L)(F_{C0})(1+f)^{i}}{(1+d)^{i}}\right) \tag{6}$$

where C_M refers to the pipe maintenance cost during its service life in terms of the *ERAC*, h_i refers to the hazard rate (failures per meter per year) for year i and is usually obtained from prediction hazard models, L denotes the length of the pipe under consideration, F_{C0} refers to the current cost (just before operation starts) to repair a pipe failure, and f, d, i and n are as defined earlier.

2.6. Hazard rate

The hazard rate (h or $h(t)$, Equation (6)) is known to follow a bathtub shape pattern for engineering structures over their service life. It mainly consists of three phases. Phase I is the burn-in period. It is a very short phase where the hazard (failure) rate starts somewhat high before it normalizes. This phase can be neglected as it is usually observed for a very short duration. Phase II has a constant failure rate due to pure random factors pertaining to pipe manufacturing, and random soil and stress conditions. Phase III is called the wear-out period and is characterized by escalating failure rates due to joint contribution of the pipe's ageing and other random factors. One way to handle such mixed distributions (while ignoring Phase I) is presented by the piecewise hazard model for linear assets, as proposed by Sun *et al.* (2011):

$$h(t) = \begin{cases} \lambda, & 0 \leq t < \xi \\ \lambda + \dfrac{\beta(t-\xi)^{\beta-1}}{\alpha^{\beta}}x, & t \geq \xi,\ \alpha > 0,\ \beta > 1 \end{cases} \tag{7}$$

where $h(t)$ is the hazard (failure) rate, λ is a constant failure rate, t is time, ξ is the start time of Phase III, and β and α are the shape and scale parameters of the Weibull distribution in Phase III, respectively.

2.7. Modeling failure rate

In this study, three materials are used as candidates for pipe materials: DICL, MSCL, and GRP. Li (18) discussed a case study from a water utility in Queensland to test hazard prediction models. He collected and analyzed 10-year failure data containing 6,687 instances of valid repair history. The empirical hazard histories for DICL, MSCL, and GRP pipes given in the bar chart in Figure 1 are used in this study to obtain the fitted piecewise hazard model curve (using Equation (7)). Although, the data are specific to Queensland, they are used for the study area since the Queensland study is comprehensive and it is hard to find other large studies in the literature. The imperial hazard histories for GRP and DICL pipes are somewhat similar, and thus, the two materials can be treated as one group to obtain the constants λ, β, and α in Equation (7). However, MSCL pipes should be treated separately. Table 1 shows the values that provide the best fitted piecewise hazard model for the two groups. Using these constants, the prediction model equation can establish the hazard rate versus pipe age (years), as shown in Figure 1. This figure is used to estimate the hazard for each year for each pipe. The result is used to estimate the maintenance cost (Equation (6)). The failure rate is multiplied by the pipe length to obtain the average number of failures:

$$N_F = h(t) \times L \tag{8}$$

where N_F refers to the number of failures in a given year, $h(t)$ is the hazard rate for the considered year, and L is the pipe length. The number of failures is multiplied by the cost to repair a failure, resulting in the maintenance cost.

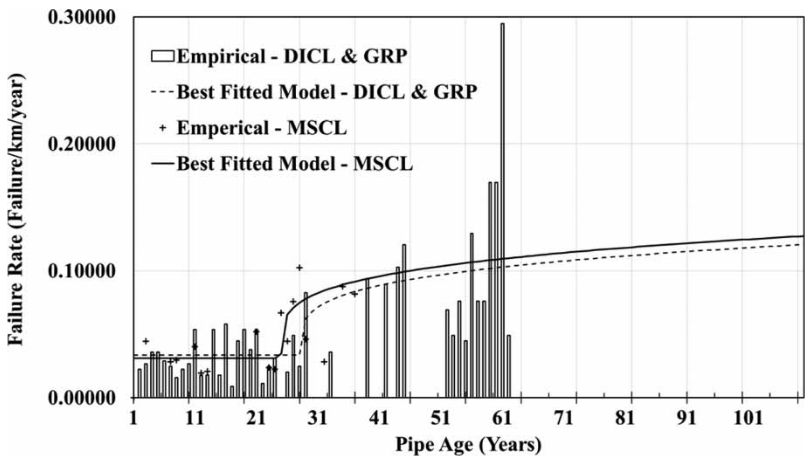

Figure 1 | Empirical hazard histories for DICL, MSCL, and GRP pipes of Queensland and modeled hazard rate (Li 2014).

Table 1 | Parameters for the best fitted piecewise hazard model for the three pipe materials

Material	λ	α	β	ξ
DICL and GRP	0.0000334	5,100	1.25	28
MSCL	0.0000312	4,900	1.25	25

2.8. Total project ERAC

Thus, the total project cost, expressed as the ERAC, is given by

$$C_T = C_{IC} + C_{Wp} + C_M \tag{9}$$

The project with the lower C_T should be chosen over those with the higher C_T. A larger pipe size translates into lower operational energy costs and vice versa. Other factors, namely pipe material and surge tank size, can directly affect C_T. Thus, one needs to search for the optimum solution (i.e., find alternatives with the least C_T), provided hydraulic constraints are not violated.

3. CASE STUDY

3.1. Project description

In this study, a real-world project is used to obtain a 'global optimum design'. This case study analysis is useful in assessing the efficacy of the proposed optimization approach. In this real-world project, raw water is obtained from a deep-well aquifer and pumped to a location close to Najran City in southern Saudi Arabia. The length of the pipeline is 109.2 km. This is one of several similar projects being carried out by the Saudi Ministry of Environment Water and Agriculture (MEWA). Because of the extremely difficult topography, three intermediate pumping stations are used. Well fields deliver raw water to tank A, and then, pumps are used to pump water from tank A to tank B, from tank B to tank C, and from tank C to tank D, all of which are located close to Najran City. Figure 2 shows a schematic diagram of the system. The normal required flow rate is 2,083 m^3/h. Table 2 summarizes a few key parameters for this real-world project.

The following water parameter values were used:

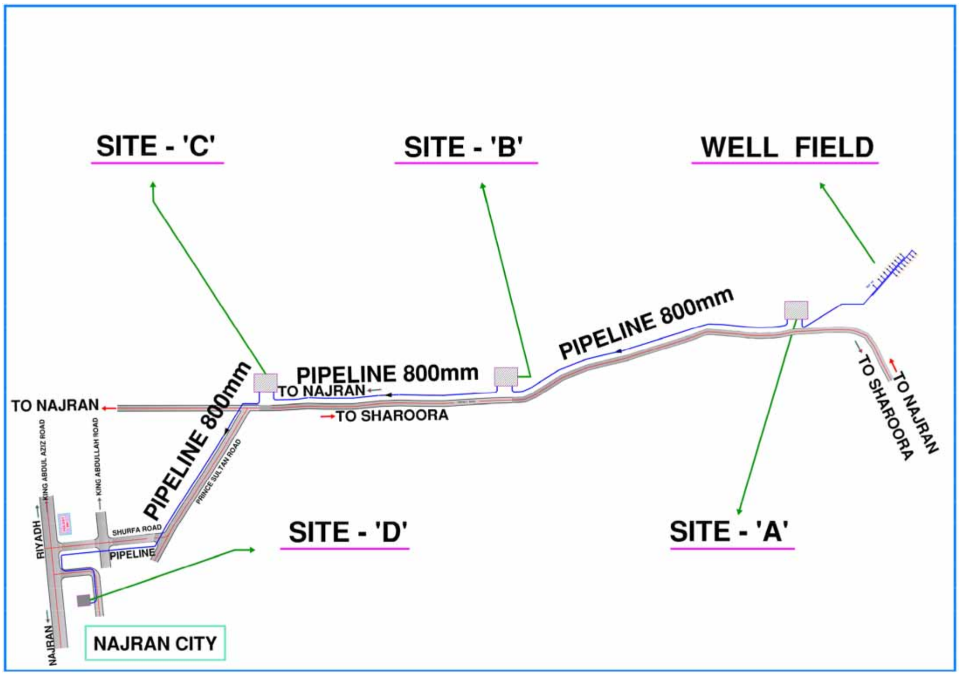

Figure 2 | Schematic of the system considered in the case study.

Table 2 | Parameters of the pipelines installed in the case study project

Pipeline	Pipe material	Length (m)	Diameter (mm)	Pipe thickness (mm)	HWC[a]	Wave speed (m/s)	Pump rated head (m)	No. of pumps
A-B	Ductile iron	43,572	800	11.7	130	1,072	200	4
B-C	Ductile iron	38,502	800	11.7	130	1,072	200	4
C-D	Ductile iron	27,133	800	11.7	130	1,072	135	3

[a]Hazen–Williams coefficient.

Temperature = 50 °C
Density = 990.2 kg/m^3
Kinematic viscosity = 0.605E − 06 m^2/s
Bulk modulus = 0.2290E + 10 N/m^2

3.2. Hydraulic analysis

3.2.1. Pipeline profiles

Figure 3 shows the pipeline profiles, steady-state hydraulic grade lines (HGLs), and maximum and minimum HGLs recorded from a complete transient flow simulation for the three pipelines. The top chart is for pipeline A-B, the middle chart is for

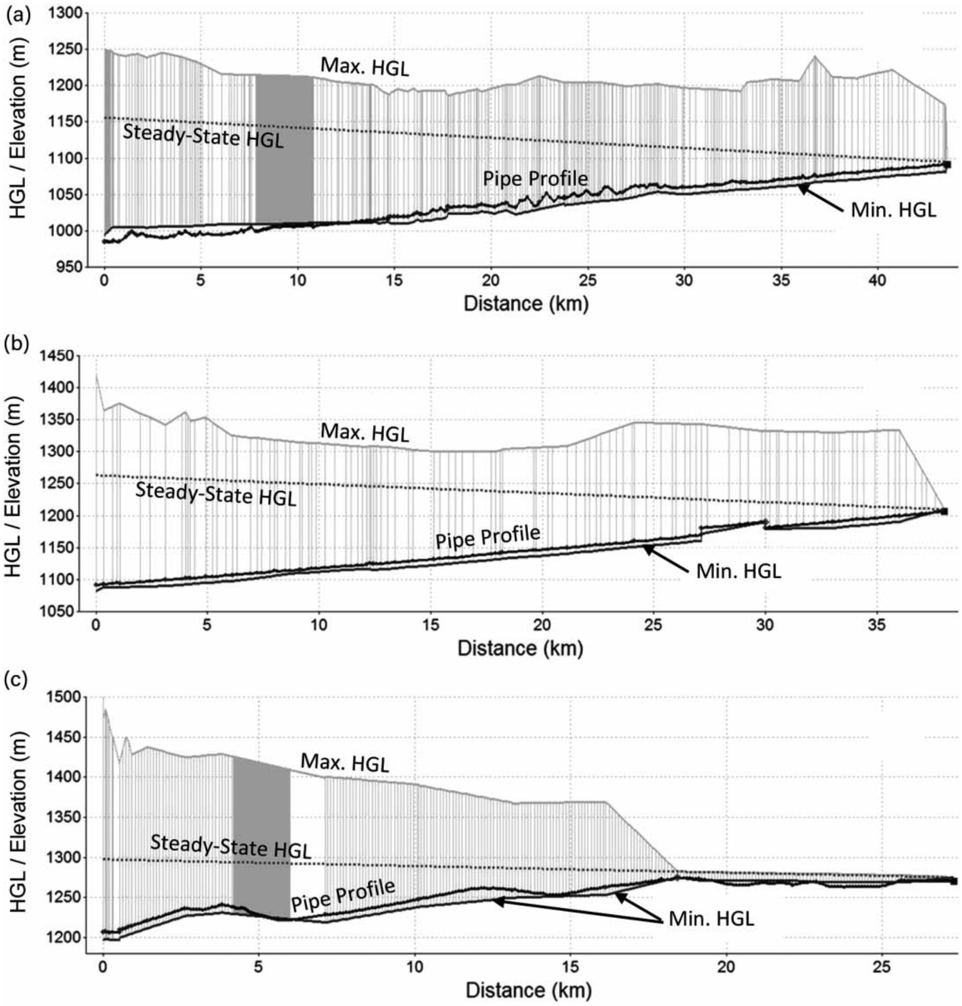

Figure 3 | Steady-state, maximum, and minimum hydraulic gradelines (HGLs) without protection: (a) pipeline A-B, (b) pipeline B-C, (c) pipeline C-D.

pipeline B-C, and the bottom chart is for pipeline C-D. The maximum elevation difference between the highest and lowest points is approximately 105 m for pipeline A-B, 115 m for pipeline B-C, and 68 m for pipeline C-D. From an hydraulic point of view, these values are considered to be extremely large changes in profiles. Thus, the construction of intermediate groundwater tanks was suggested by the hydraulic studies conducted by the MEWA.

3.2.2. Hydraulic grade lines

Figure 3 shows the maximum and minimum HGLs without protection. These HGLs were obtained using steady-state conditions and transient flow simulation. Each point along the maximum HGL shows the maximum pressure head recorded at that point throughout the steady-state and transient flow simulation time. Each point along the minimum HGL represents the minimum pressure head recorded at that point throughout the simulation period.

4. RESULTS AND DISCUSSION

All cost components mentioned earlier were summed to obtain the ERAC for each trial solution. For the case study under consideration, Table 3 lists the actual ERAC for each of these components. The costs for each item were estimated using the methods discussed earlier in this paper (Equations (4)–(9)). The objective was to search for the least expensive design using the optimization procedure described previously and to compare its costs to the actual costs.

When the optimization routine was run, it identified many design alternatives, and the costs of some designs were less than the actual as-built costs, as summarized in Table 3. Some of these alternatives were rejected because they violated one or more of the pressure and/or velocity constraints. In this study, the steady-state flow conditions are used to check the velocity constraints (0.8 to 2.5 m/s) and a transient event is used to check the nodal pressure constraints (−0.5 to 25 bar). The five cost components of each acceptable design (see Equation (9)) were obtained in terms of the NPV, converted to the ERAC, and added to obtain the total ERAC (C_T in Equation (9)). Figure 4 shows a list of solution alternatives for pipeline B-C arranged in ascending order based on the C_T values. For readability, only the best 160 trial solutions were considered. Figure 4 (top panel) shows the most important hydraulic parameters and constraints for each of the solutions, such as the minimum and maximum pressure resulting from both the steady-state flow analysis and the imposed transient event (discussed earlier). It also shows the initial gas volume – IGV (for the surge tank) and its lower and upper bounds. Furthermore, the figure depicts the required pump pressure as well as pump power for each solution. Figure 4 (bottom panel) shows the cost aspect for the same trial solutions in the order depicted in the upper panel of the figure. The horizontal axis represents the trial solution number. The secondary vertical axis shows the penalty applied because of constraint violation. The primary vertical axis denotes the five cost components mentioned earlier (see C_T in Equation (13)). The first reading in Figure 4 (bottom panel) shows the optimal ERAC (US$0.63 million). The total cost includes the ERAC of the five cost components as well as the penalty cost. Note that when the pipe cost reduces due to a smaller diameter selection, the pump initial cost and energy cost increase, and vice versa. It is clear that when the pressure exceeds the lower or/and upper bound(s), the penalty cost increases. The bottom of the figure shows the material type as a letter (M for MSCL, G for GRP, and D for DICL) and the pipe diameters (8 for 800 mm, 9 for 900 mm, 10 for 1,000 mm, and 12 for 1,200 mm). The material and diameter symbols are depicted in two rows each for clarity. The first best 12 solutions are attributed to the MSCL pipe of diameter between 900

Table 3 | Estimated as-built equivalent annual costs (ERAC) (US$, millions) for the pipelines of the case study under consideration

Component cost/pipeline	A-B (L = 43.6 km)	B-C (L = 38.5 km)	C-D (L = 27.1 km)
Pipe with installation/transportation	28.930	25.570	18.020
Surge tank	0.240	0.190	0.110
Pump initial cost	1.120	1.120	0.570
Pump energy cost	36.090	36.090	18.260
Pipe maintenance	2.680	2.340	1.680
Total cost (NPV)	69.060	65.310	38.640
Real rate-based annuity factor (A_f) from Equation (6)	70.436	70.436	70.436
Total cost (ERAC)	0.980	0.930	0.550

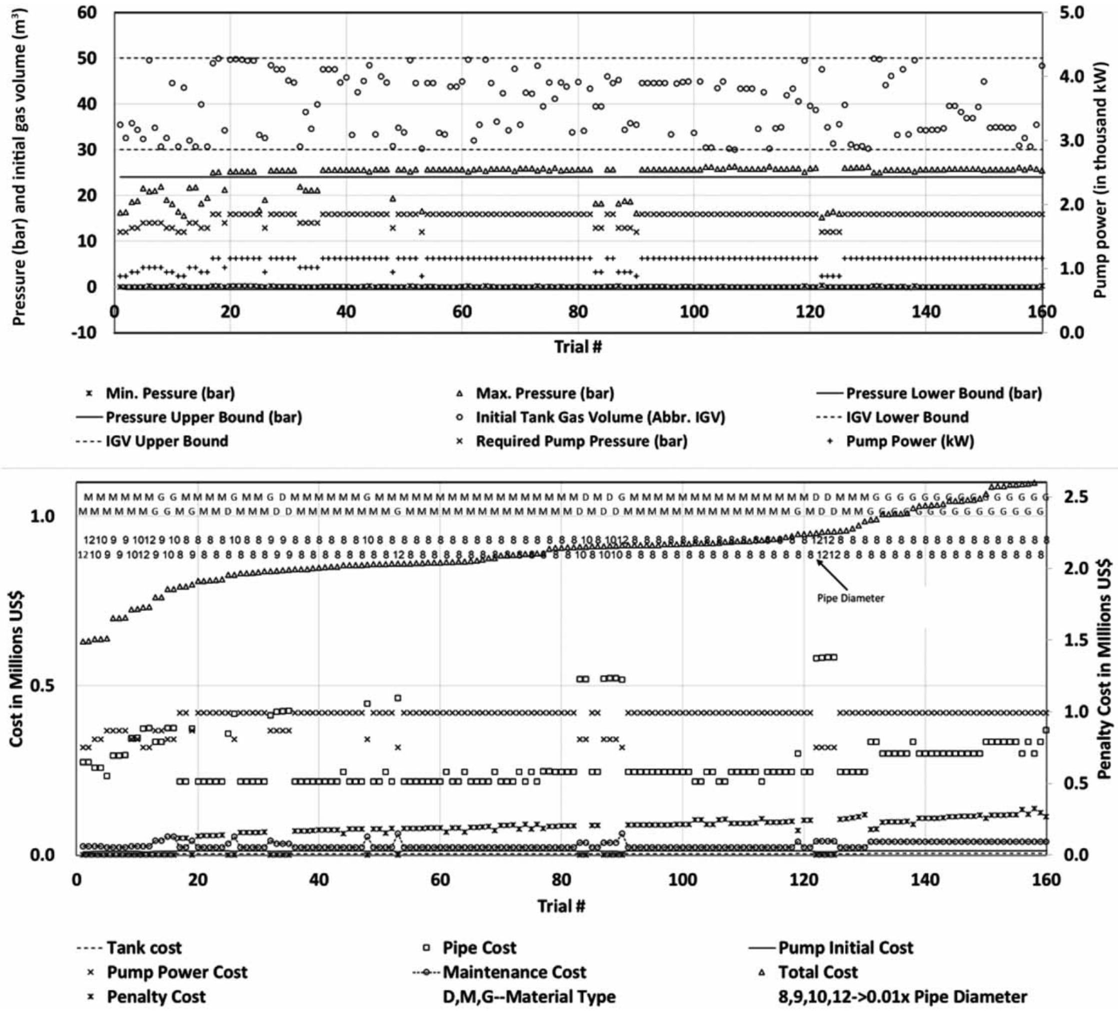

Figure 4 | Sorted list of solution alternatives for sample optimization run for pipeline B-C.

and 1,200 mm. The lowest cost design alternatives for each pipe material are listed in Table 4. It is evident that when selecting the DICL material, the revised design resulted in 8.5% savings compared to the as-built project cost, although the same pipe material was used. This result is attributed mostly to the over-designed pump power as well as cost optimization of the surge tank size and connection resistance. The overall saving achieved with the GRP pipe is 16.3%. Using MSCL material resulted in a remarkably high saving of 31.1% in terms of the project ERAC compared to the data for the as-built DICL material. In other words, selecting DICL over MSCL could result in an increase of 33.2% in cost (with both designs optimized). This is mainly due to the lower cost of the MSCL pipe material.

Table 4 | Optimal cost in ERAC (US$, millions) obtained for each pipe material

Pipeline	A-B	B-C	C-D	Total project cost	Overall savings (%)
Estimated as-built ERAC (US$, millions)	0.98	0.93	0.55	2.46	
DICL	0.90 (D = 800 mm)	0.83 (D = 800 mm)	0.52 (D = 800 mm)	2.25	8.5
GRP	0.82 (D = 900 mm)	0.76 (D = 900 mm)	0.48 (D = 800 mm)	2.06	16.3
MSCL	0.66 (D = 1,200 mm)	0.63 (D = 1,200 mm)	0.40 (D = 900 mm)	1.69	31.3

Figure 5 shows the ERAC if only one of the three pipe materials (DICL, GRP, or MSCL) is considered for each of the three pipelines. The top panel shows the ERAC if only DICL material is available to install. The middle and bottom panels show the ERAC for GRP and MSCL, respectively. Unifying the material in this manner allows interpretation of the effect of the diameter on the cost. The first five bars in the top panel relate to pipeline A-B. The first bar is the cost estimate for the as-built pipeline (DICL of 800 mm diameter). The other four bars denote the four pipe sizes, as shown in the legend. The bars show the least-cost design (minimum C_T) for each pipe size that could theoretically be used without violating the project constraints. The top panel shows that the best pipe size when using DICL material is the 800 mm for all the three pipelines (A-B, B-C, and C-D). It is clear from Figure 5 (top panel) that to reduce the cost for DICL, which entails a high material cost, a pipe of a smaller diameter must be used (despite the higher energy cost). Figure 5 (bottom panel) shows that when MSCL material is used, the optimum diameter for A-B and B-C is 1,200 mm, while the optimum diameter for pipeline C-D is 900 mm. A clear pattern emerges: the less expensive the material, the more economical it is to select higher diameter pipes and save on the energy cost. However, for shorter MSCL pipes (pipeline C-D), smaller diameters will be less costly (even at the expense of power). The optimal GRP cost lies approximately midway between that of DICL and MSCL in the sense that the best pipe size is 900 mm for A-B and B-C and 800 mm for C-D.

Figure 6 shows the effect of material on pipe cost when considering a constant pipe diameter. Figure 6(a) shows the cost if three materials are available for selection and only pipes of 800 mm diameter are allowed. It is clear that the least expensive material for all the three pipelines (A-B, B-C, and C-D) is MSCL, followed by GRP. Figure 6(b) shows the cost when considering a constant pipe diameter of 900 mm. Here too, MSCL is the least expensive material. The same conclusion applies for

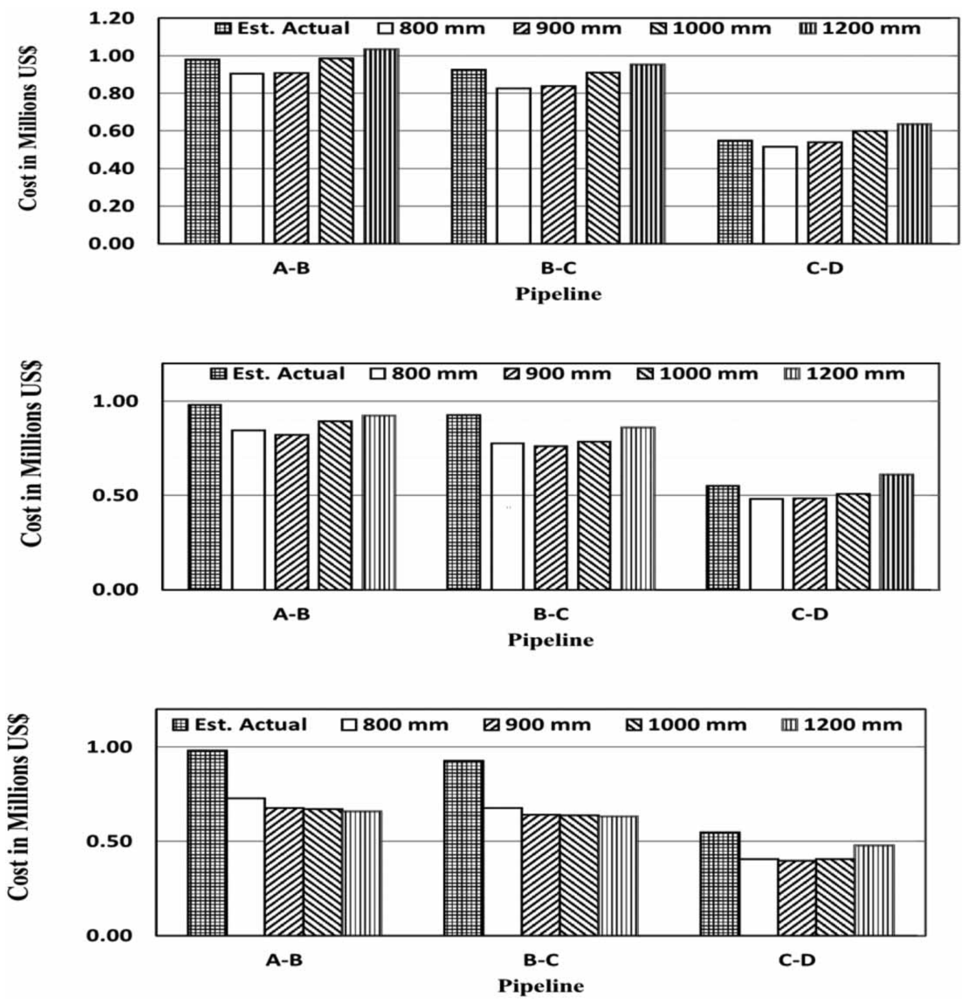

Figure 5 | Project cost if one material is imposed on the design: DICL (top), GRP (middle), and MSCL (bottom).

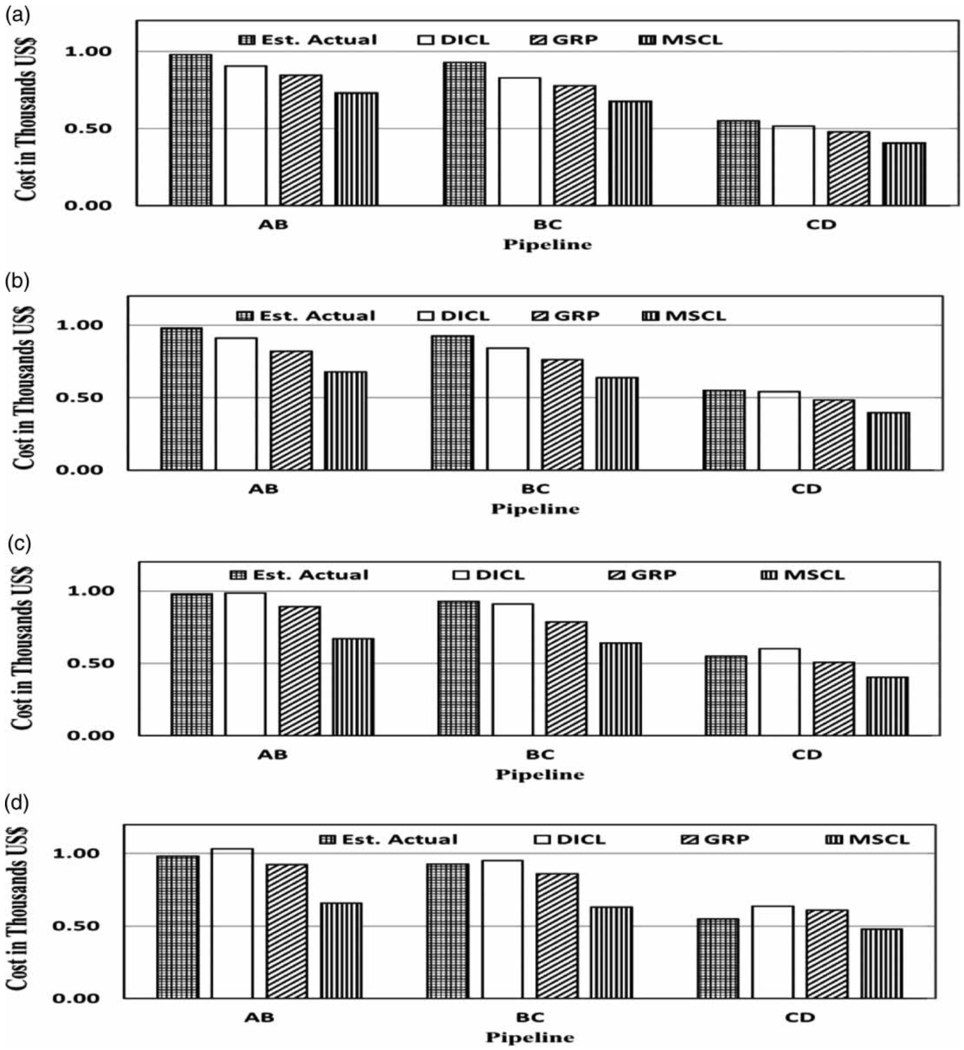

Figure 6 | Project cost if a single diameter is imposed on the design for the whole project: (a) 800 mm, (b) 900 mm, (c) 1,000 mm, and (d) 1,200 mm.

pipes of diameter 1,000 mm and 1,200 mm (Figure 6(c) and 6(d), respectively). When selecting DICL pipes of diameter 800 mm and larger (both using the optimized design), one would pay additional cost of 24, 23, and 27% for pipelines A-B, B-C, and C-D, respectively, as seen in Figure 6(d). Choosing the 'least expensive diameter' of MSCL over that of DICL could save 27, 24, and 23% of the total cost for pipelines A-B, B-C, and C-D, respectively. Thus, for this case study, the longer the pipeline, the higher the saving if one were to use higher diameter MSCL over any other material. Similarly, selecting MSCL over GRP can result in savings of 20, 17, and 17% for these pipelines, respectively.

It is crucial to note that if the NPVs of the costs is used for comparison between project alternatives that have different lifespans, one may unintentionally select more expensive project alternatives. Thus, considering alternatives for projects with different lifespans should be handled carefully, either by using the replacement chain method or the ERAC.

5. CONCLUSIONS

Given the huge expenditure involved in building pipelines, cost optimization is an important issue in the global construction industry. This study analyzed pipeline optimization in a more comprehensive manner than previous studies by extending the solution search space to include the pipe diameter, pipe material, surge tank size, pump initial cost, energy cost, and maintenance cost throughout the project service life. Instead of using the NPVs of cost to compare project alternatives, this study used the equivalent real annual cost, which is a precise tool to analyze alternatives with different lifespans in the presence of inflation. A GA was implemented to search for the optimum cost of the pipeline material, installation, and maintenance. In this approach, the GA-suggested design alternative is accepted as a candidate solution if it does not violate pressure and velocity constraints during steady-state flow or during unsteady flow associated with an extreme event (e.g., stoppage of upstream flow in 2 s). A real-world project was used as a case study. The results showed that the proposed 'global optimization' approach could lead to remarkable savings, at least for projects similar to the case study described in this paper, namely, a long pipeline with a diameter of 800 mm. The analysis of the case study showed that for certain low-cost pipe materials and in specific cases, it is possible to considerably reduce the project cost by selecting a larger-diameter pipe to lower the pump energy cost over the project service life. This is more obvious when the pipe initial cost (material/installation) is lower. Applying approaches with extensive search for better solutions, such as the proposed approach, to pipeline projects may result in significant savings without sacrificing quality. Considering hydraulically equivalent alternatives and using the correct tool to recognize the changing value of money in this type of analysis will facilitate unbiased comparisons of costs. Such an approach can offer a very clear and objective choice, free of personal bias towards any one alternative (e.g., pipe material) based on partial knowledge or unjustified hypotheses. This paper presented only one case study comprising large pipe diameters, and therefore, applying the approach to projects using smaller diameters is advisable. This would yield a more comprehensive assessment of the extent of variation in pipeline project costs when the project is analyzed with a wide search space for all types of parameters that could affect its overall cost.

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DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

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