Lifecycle cost optimization of pipeline projects

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ABSTRACT

Lifecycle cost optimization for a pipeline network with medium-sized pipes is performed considering steady and unsteady flow conditions. Genetic algorithms are used to generate a wide range of hydraulically acceptable solutions and search for the most economical solutions. The impact of each cost component on the total cost is determined in this study. The decision variables include the pipe diameter, pipe material, pipe pressure rating, surge tank size and operational and maintenance costs over the project service life. A real-case project is presented to crosscheck the suggested procedure. Significant cost variations are observed, even between equally acceptable designs. Furthermore, the operational cost has a deterministic effect on the parameters of the optimum solution. Compared to conventional design wisdom that focuses on reducing the pipe diameter as much as possible to reduce the project cost, this approach demonstrates that significant savings in pipeline project costs can be achieved by carefully investigating all possible design alternatives under steady and unsteady flow conditions.

Key words | global optimization, lifecyle cost analysis, lifecyle cost optimization, pipeline cost estimation, pipeline optimization, pipeline projects

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HIGHLIGHTS

- Using all the relevant decision variables in the optimization.
- Using the lifecycle cost concept rather than the initial cost when comparing alternatives.
- Using the average inflation rate to predict maintenance and replacement cost in the future.
- Using the average interest rate to obtain the present value of all the cost components.
- Using steady and unsteady flow conditions to accept or reject a given network design.

ABBREVIATIONS

D, DICL	Ductile iron clay-lined
G, GRP	Glass reinforced plastic
M, MSCL	Mild steel clay-lined
C-H	Site C to Hussainia pipeline
H-M	Hussainia to Muntashar pipeline
M-B&T	Muntashar to Habuna and Thar pipeline

INTRODUCTION

With the ever-increasing cost of pipelines and pipe network projects, it has become increasingly important to make every possible effort to optimize the cost of such projects. Under-design issues can result in undesirable and costly pipe failures, and over-design can result in wasted resources (Kanakoudis 2004a). Both over-design and under-design issues can be avoided by incorporating an efficient search for an optimum design with the lowest lifecycle cost.

Transient events can result in above- and below-normal pressures at certain points in a pipe network or a pipeline system (Kanakoudis 2004a). Without proper protection devices installed at appropriate locations, high surge pressures can lead to catastrophic failures. Subatmospheric pressure conditions resulting from these transients can

cause leaky joints and introduce contaminants into the pipe system from the environment surrounding the pipes (Jung *et al.* 2007; Kanakoudis & Tsitsifli 2017; Tsitsifli & Kanakoudis 2018). Water hammer protection devices are mandatory, but they usually represent a small fraction of the pipe network costs. In some of the literature, pipe networks have been designed for steady-state flow conditions, but it has been proven that this approach is not accurate (Jung & Karney 2006).

Pipe network optimization has been discussed in the literature to varying degrees. Most studies have considered certain objectives or aspects of decision variables and ignored other important factors. Some studies have addressed pipe network optimization using the pipe diameter as the only decision variable. Both steady-state and unsteady flow conditions have been considered but without the use of surge pressure protection devices (Djebedjian *et al.* 2005; Afshar 2006). The optimization of surge protection devices has been discussed in some studies. For instance, if there is a high point along a pipeline, a simple surge vessel can be used for protection. This approach can reduce the overall cost of the pipeline. If, however, the design requires an impractically large surge tank, a small surge tank and air valves can be combined (Matringe 2004). It is possible to replace a surge tank connecting the apex of a pipe with an air inlet valve combined with a double-acting air valve with a low air discharge capacity (Espert *et al.* 2008). Lingireddy *et al.* (2000) showed how a specific surge tank design can provide an optimal set of decision variables while not violating the preset pressure constraints.

Jazayeri Moghaddas *et al.* (2016) addressed the issue of sizing air chambers and air inlet valves and identified the best locations to optimize the cost of transient protection in pipelines. Jung & Karney (2013) considered a two-step optimization problem. In the first step, particle swarm optimization (PSO) is implemented to find the nodes with the worst-case transient loading condition. In the second step, optimum pipe sizes are found using dual-objective optimization to minimize the cost and likelihood of needing critical transient events. Jung & Karney (2006) addressed design optimization using a genetic algorithm (GA) and PSO. Different combinations of surge protection devices have been used, and the GA and PSO techniques have

been implemented to find the optimum locations and sizes of protection components.

Some studies have addressed pipe network optimization under unsteady flow conditions. Laine & Karney (1997) used a simple pipe system consisting of a pipe connecting a pump to a storage tank to demonstrate their optimization procedure. A complete enumeration technique combined with a probabilistic selection approach has been used in both steady-state and unsteady-state flow analysis. Other research has considered additional important objectives and decision variables to optimize pipe networks. For instance, Farmani *et al.* (2005) implemented an improved nondominated sorting GA method to address three factors: (1) the total cost of network expansion and rehabilitation that encompasses the initial and pumping costs; (2) the resilience index; and (3) the minimum surplus nodal pressure for the optimal rehabilitation strategy with expansion for any network. Creaco *et al.* (2014) used a procedure to optimally design a pipe network considering objective functions for the (1) initial cost, (2) operational cost and (3) pressure-reducing valve cost. Jayaram & Srinivasan (2008) proposed a multiobjective formulation to optimize the design and rehabilitation of pipe networks with the objective of minimizing the lifecycle cost and maximizing network performance. The lifecycle cost components included are the initial pipe cost, the pipe replacement cost, the cost of cleaning and lining existing pipes, the pipe repair cost and the replaced pipe salvage value. Ahmetović & Grossmann (2011) discussed a general superstructure and a model for the global optimization of integrated water networks. The model consists of multiple sources of water, water use processes, wastewater treatment and pre-treatment operations. All feasible interconnections are considered, and multiple sources of water can be used. The efficiency of the proposed model was tested using several examples. Tian *et al.* (2018) developed a subsystem nonlinear programing model to optimize the layout of a pumping station and sewage pipe network design. Then, the subsystem model was expanded to a large-scale complex nonlinear programing system model to find the minimum overall annual cost of the pumping station and network of all pipe segments. A comparative analysis was performed using the sewage network in Taizhou City, China, as a demonstration example.

Different cost optimization techniques, such as the linear programing gradient (Alperovits & Shamir 1977; Fujiwara *et al.* 1987; Kessler & Shamir 1989; Bhave & Sonak 1992; Samani & Zangeneh 2010) and nonlinear programing (Fujiwara & Khang 1990; Varma *et al.* 1997), have been used to search for the lowest cost design alternatives. Other studies have used dynamic programing for water distribution network (WDN) optimization (Schaake & Lai 1969; Cheng *et al.* 2019).

Heuristic algorithms, such as GA (Simpson *et al.* 1994; Al-Khomairi & Imam 2000), ant colony optimization (Cunha & Ribeiro 2004; Zecchin *et al.* 2006; Bahoosh *et al.* 2019), Tabu search (TS) algorithm (Maier *et al.* 2003), simulated annealing (Cunha & Sousa 1999), scatter search (Lin *et al.* 2007), differential evolution (Arunachalam & Simonovic 2010), shuffled complex evolution (SCE) (Liong & Atiquzzaman 2004), artificial immune system (Eryigit 2015) and the jazz improvisation process (Geem 2006), have been implemented recently to solve pipe network optimization problems.

Pipeline cost optimization can be performed in the three following ways.

1. Lifecycle analysis for a pipeline is performed based on steady-state flow conditions without protection devices. This is the least-expensive solution but has a high risk of pipe failure.
2. After completing the design using the steady-state flow conditions to find the optimum pipe diameter and material, protection devices are added to the system to keep the pressure within a predetermined range. This traditional method is the costliest approach.
3. Lifecycle analysis is performed with both steady and unsteady flow conditions for each of the solution alternatives. In other words, transient analysis is included in the lifecycle analysis.

The last approach is a 'global approach' and is less costly than (1) and (2) above. This global approach is applied in this study. Furthermore, unlike the studies discussed above, the objective of this study is to consider all the major factors that can affect the lifecycle cost of pipeline projects. The same principles can be applied to pipe networks. A handful of variables that considerably affect the cost of a pipeline project are called decision variables. These decision variables include the pipe diameter, pipe material, pipe pressure rating and surge tank volume. The volume of the surge tank is influenced by the initial gas volume of the surge tank and the connection resistance of the tank. These two variables are the primary variables that control the overall size of a surge tank. In addition to considering these initial costs, this study aims to consider the operational and maintenance costs for a predetermined project service life. The proposed approach is applied to a real-case project to check how each of the decision variables contributes to the overall cost of the project and how it can affect the optimum solution. This study focuses on medium-sized pipelines (diameters of 300–600 mm).

PROCEDURE

A pipeline extending over a long distance can have many different design alternatives, ranging from economical to drastically over-designed. It is important to evaluate each design alternative and compare it to other designs to select the most appropriate and least costly design. This concept involves setting the necessary constraints. The primary constraints are the steady-state pipe velocities and the transient nodal pressures. These two constraints must be within certain preset bounds. If the constraints are not violated, the design is acceptable and is technically equal to other acceptable designs. A GA code has been written and integrated with software commonly used for commercial steady and unsteady pipe flow analysis. The integrated package searches for the possible optimum design in the search space. The GA code generates random values for each of the decision variables, analyzes the resulting solution vector for both steady and unsteady flow conditions and checks for any violations of the preset constraints. The model also performs mutation and crossover for the best solutions to search for even better solutions. The decision variables considered in this study are the pipe diameter, pipe material, pipe pressure rating, initial surge tank volume and inlet/outlet connection resistance of the surge tank. The cost of each solution vector is estimated using actual price quotes supplied by major contractors. If constraints are violated, a penalty function is applied, and a certain cost is added to the project cost. The penalty function thus removes the solutions with constraint violations,

as they are more expensive than other solutions with zero penalties. All the costs are obtained in terms of the present value. Once the software package obtains all possible solutions, the initial and operational costs of the pump and the pipe maintenance cost are evaluated and added to the cost established by the software package to determine the total cost. Solution alternatives are compared using the present value of the total cost. The following sections explain how the different costs are estimated.

The decision variables considered in this study are the pipe diameter, pipe pressure rating, pipe material, initial gas volume of the surge tank and surge tank connection resistance. The first three decision variables can take some predetermined, technically practical values. However, the latter two values should take specific values that are selected based on suitable and available pipe data. The state variables are the transient pressure at all nodes and the steady-state velocities in all pipes. The constraints enforced in the analysis are the transient nodal pressures, the steady-state pipe velocities, the initial gas volume of the compressor vessel and the connection resistance. These values should be within the preset upper and lower limits. In this study, steady-state flow conditions are used to check the velocity constraints (0.8–2.5 m/s), and a transient event is used to check the nodal pressure constraints (−0.5 to 25 bar). Pump tripping is the most common and undesirable transient event that can occur in pipeline projects. In this study, a transient event is considered by imposing a full flow stoppage (just downstream of the pump) in 2 s. In fact, this event is more severe than a pump trip. The nodal pressure constraints are checked using the results for this transient event. The total cost for each design alternative is the sum of the three cost components: the initial cost, the operational cost and the maintenance cost. All these costs are estimated for each year of the project service life, expressed in present value and compared. The following sections discuss how each of the cost components is estimated.

The first stage of optimization concerns the initial costs. An integrated software package is used. The GA searches for and suggests as many solution alternatives as possible, considering the pipe material and installation costs and the pump and surge tank initial costs. The aforementioned decision variables are considered in this stage of optimization to generate the design alternatives. Pump and pipe prices are obtained from actual quotes given by major contractors. The initial pipe price is given per m of pipe length, and the pump price is estimated using the average price per kWh (i.e., $250/kWh) with an 80% assumed pump efficiency. After the initial costs for the pipes, pumps and surge tanks are computed for all possible solutions generated by the GA subroutine, further computations are needed to find the future operational cost of the pump and future maintenance cost of the pipe for the project service life expressed in present value. The current pump power cost is US$0.0408/kWh. The average inflation rate is applied to estimate the future power cost for each year of the pipe service life; then, each of these annual costs is expressed in the present value using the assumed average interest rate.

The maintenance cost is the third cost component and is added to the two previous cost components discussed above to find the total project cost. Some studies have considered preventive maintenance optimization. Techno-economic analysis that takes into account all sorts of costs pertinent to the repair or replacement of trouble-causing parts of a system has been implemented in water distribution systems (Kanakoudis & Tolikas 2001; Kanakoudis 2004b; Kermanshachi *et al.* 2019). Other studies have performed lifecycle cost estimation to account for the different aspects of corrective maintenance during the project service life (Durairaj *et al.* 2002; Office of Government Commerce 2003; Christensen *et al.* 2005). Some aspects are expected to be more important than others depending on the circumstances. For instance, in places where labor is inexpensive, labor costs will be small compared to material and power costs, and when the material cost increases globally, this might become the most costly component.

In this study, the expected (based on previous studies) lifecycle corrective maintenance will be estimated and added to the two previously mentioned cost components (initial and operational costs) to obtain the overall project cost. Three pipe materials are considered: ductile iron clay-lined (DICL), glass fiber reinforced plastic (GRP) and mild steel clay-lined (MSCL) pipes. The pipe service life assumed in this study for all three pipe materials is 50 years. The pump is assumed to have a service life of 25 years. Thus, the project cost over 50 years is estimated with the pump set replaced

once. The cost of pipe maintenance is estimated using a case study discussed in the literature. Li (2013) presented a case study of a water utility in Queensland to test hazard prediction models. A 10-year failure data set containing 6,687 instances of valid pipe repair was investigated. The empirical hazard histories for DICL, GRP and MSCL pipes shown in the bar chart in Figure 1 are used in this study to obtain the fitted piecewise hazard model curves shown in the same figure. The imperial hazard histories for DICL and GRP pipes are similar, and thus, the two materials can be treated as one group. These curves are used to estimate the hazard (Number of failures/year/km) for each year of the pipe history and thus compute the cumulative maintenance cost for each pipe material. The pipe repair cost for each year of the project service life is estimated using the current repair cost (for each material) and the average inflation rate. Then, the average interest rate is used to express the annual repair costs in the present value. The total maintenance cost is obtained by summing these values. The current pipe repair costs for each pipe material are obtained from actual quotes given by major contractors. In this study, the future costs of replacing the pump (once, after 25 years) and the future costs of pipe maintenance are established using a 2.8% average inflation rate. Then, an average interest rate of 3.7% is used to express the costs in the present value for easy comparison.
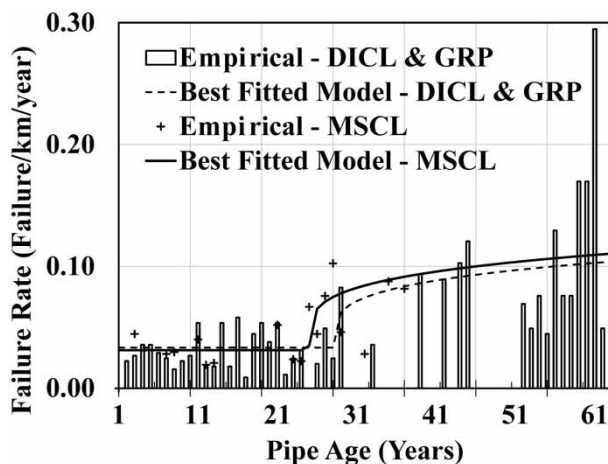

Figure 1 | Empirical hazard histories and modeled hazard rate for the three pipe materials in the case study.

CASE STUDY

This case study applies the suggested lifecycle optimization procedure to a real system: a recently constructed pipeline project near Najran City, which is located in the south region of Saudi Arabia in a mountainous region with extreme topography. The layout of the system is shown in Figure 2. Potable water is pumped from site C in the Najran field using three pumps operating on a duty/duty/standby basis to deliver a maximum flow of 807 m^3/h along a 400 mm, 47.54 km long DICL pipe ending in an underground storage tank in Hussainia. Along this main, three locations are supplied with water: Tasalal (41.6 m^3/h), Najran University (166.6 m^3/h) and Mashalia (62.5 m^3/h). The remaining flow (536.3 m3 /h) discharges into the Hussainia storage tank, as shown in Figure 2. Potable water is transferred from the Hussainia storage tank using three pumps on a duty/duty/standby basis to deliver a flow of 521 m^3/h along a 400 mm, 29.3 km long DICL main. Finally, the potable water is transferred from the Muntashar underground storage tank to the Habuna and Thar underground storage tanks using three variable speed pumps operating on a duty/assist/standby basis to deliver a flow of 417 m^3/h along twin 300 mm DICL supply mains: one is 17.4 km long and transports water to Habuna at 271 m^3/h, and the other is 13.1 km long and delivers water to Thar at 146 m^3/h. Henceforth, the notations C-H, H-M and M-B&T are used for the abovementioned pipeline segments, including site C to Hussainia, Hussainia to Muntashar and Muntashar to Habuna and Thar, respectively.

Figure 3 shows the pipeline profile for the main pipelines (excluding branches) of this project from Site C to Habuna. Additionally, the maximum and minimum HGLs are illustrated. The minimum HGL is the line connecting the minimum HGL values along the pipeline obtained from simulating the steady and unsteady flow conditions. Similarly, the maximum HGL is the line connecting the maximum HGL values. The protection used in this simulation is a surge tank (compressor type) just downstream of the pump. The top panels in Figure 3 show the data history without using a surge tank, and the bottom panels show the same system when considering a surge tank just downstream of the pump. As clearly shown from the
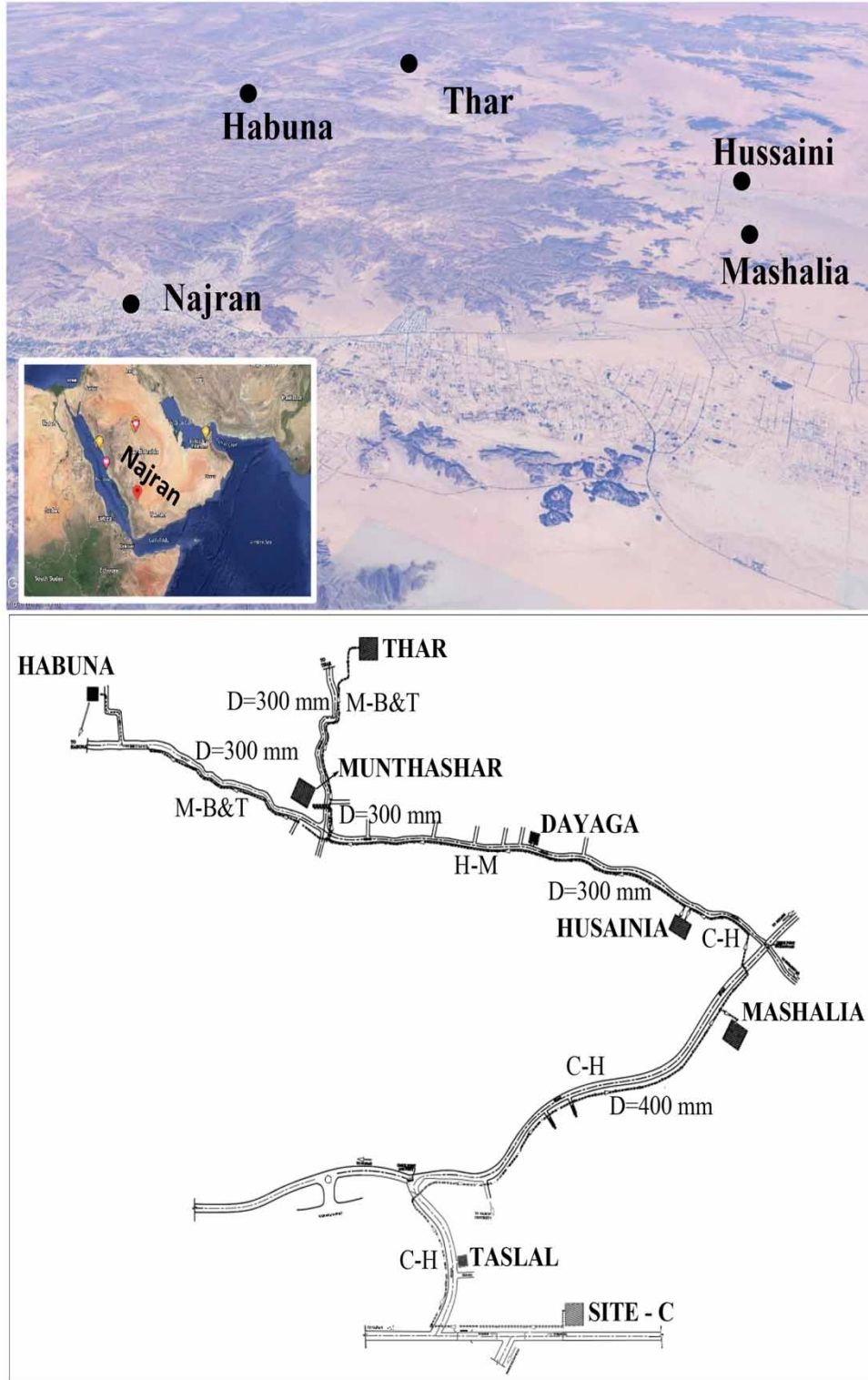
Figure 2 | Project area topography (upper half) and system layout (lower half) for the case study.

pipeline profiles in Figure 3, the complex topography results in high and low pressures; therefore, it is mandatory to use intermediate buffer tanks in Hussainia and Muntashar instead of using one set of pumps to pump water through the entire pipeline. The use of the compressor-type surge tank reduces the positive pressure and eliminates the negative pressure in some parts of the pipelines.

For this case study, the following key parameter ranges/ allowable values are used:

- Pipe fluid velocity: 0.8–2.5 m/s;
- Nodal pressure: −0.5 to 25 bar;
- Pipe pressure rating: 10, 16 or 25 bar;
- Pipe diameter: 300, 400 or 600 mm; and
- Pipe material: DICL, GRP or MSCL pipes.

It should be noted that the pipe fluid velocity range is violated for pipes with diameters that are less than 200 mm or greater than 600 mm, which is the reason for omitting pipe diameters outside the listed range.

RESULTS AND DISCUSSION

The estimated actual system present values of all the pipeline project cost components (initial, operational and maintenance costs) are shown in Figure 4. The strategy suggested in this study is used to search for the least expensive yet technically acceptable solutions that satisfy the flow rate demands and do not violate any constraints (e.g., pipe fluid velocity and upper and lower limits of the nodal pressure). All the pipes used in the actual design are DICL pipes, and their diameters in mm are shown above the total cost bar in Figure 4. It is evident from Figure 4 that the highest cost component is the initial cost of the pipe,
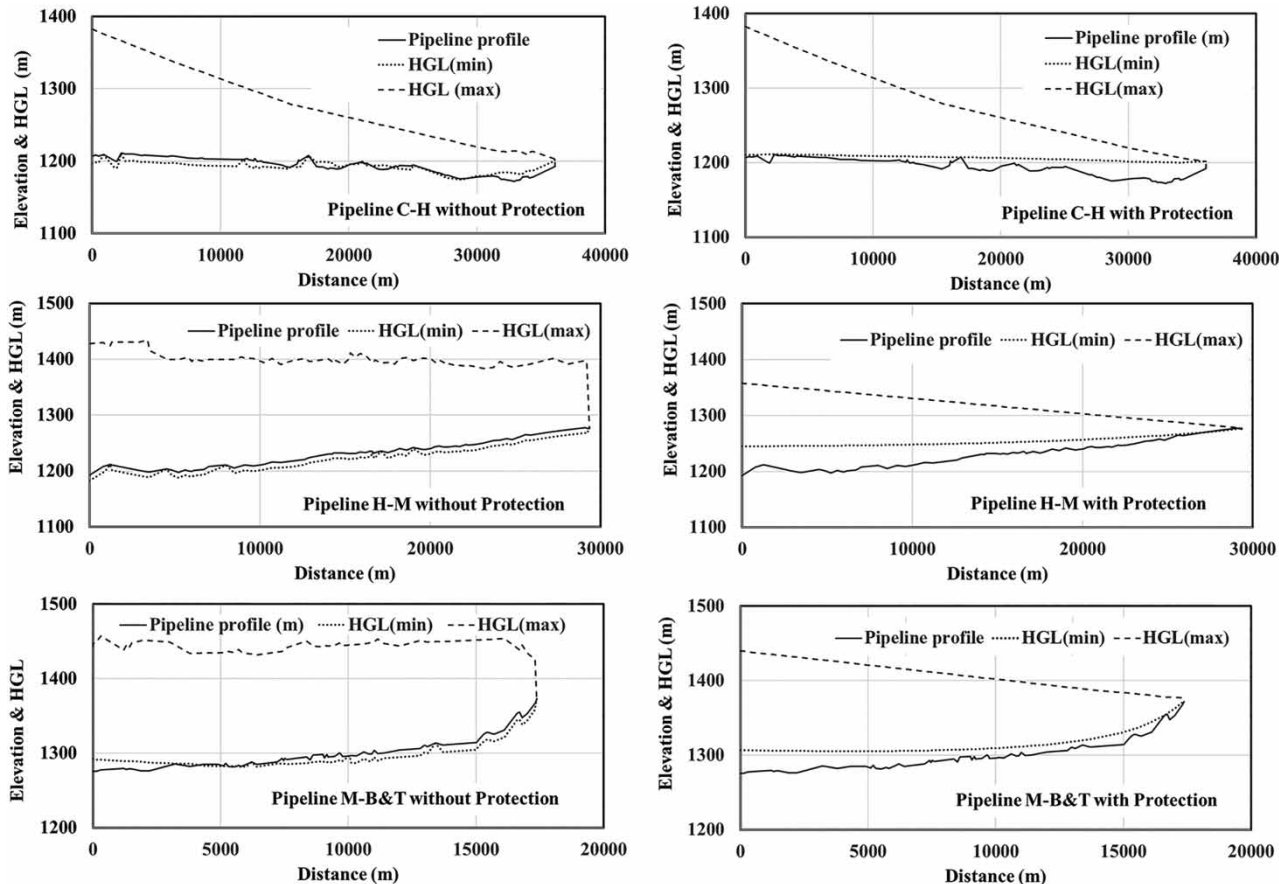

Figure 3 │ Pipeline profiles and hydraulic grade lines with and without protection.
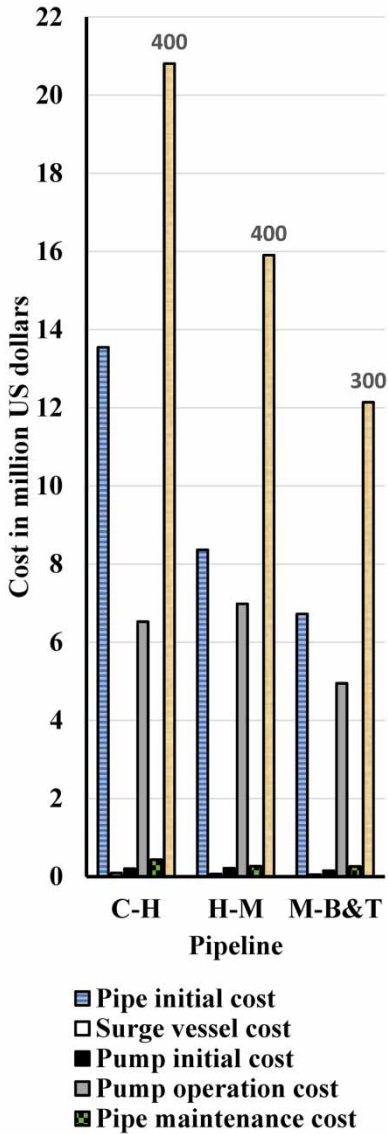
Figure 4 | Estimated cost of the actual project (with the used pipe diameter shown above the total cost bar in mm).

Figure 5 | Design output for the M-B&H pipeline.

followed by the pump power cost over the project lifecycle. This result suggests that the operational power cost plays a major role when searching for the most economical design, as will become clear later in this discussion. Figure 5 shows the output for the M-B&H pipeline. The figure shows a partial list of 40 acceptable designs arranged from the least costly to the most costly. These designs include the single most economical design for the system, which is the first one from the left. Both the top and
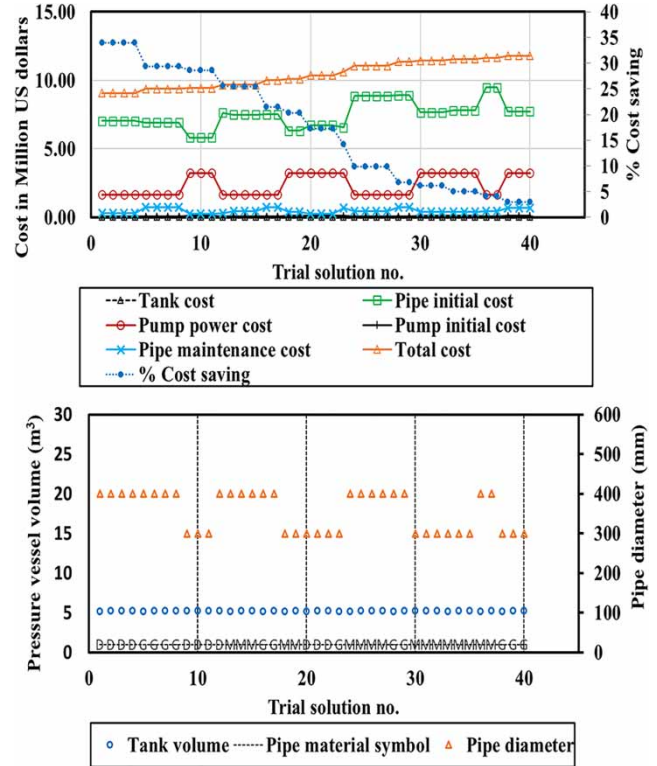
bottom panels in this figure share the same design number (solution vector), as shown below each panel. The top panel of the figure shows how much each of the cost components contributes to the total project cost. The bottom panel shows the selected surge tank volume and pipe diameter for each design. The symbols shown in the bottom panel of this figure are for the pipe material used in the trial design: M for MSCL, G for GRP and D for DICL. The optimum solution in this case costs approximately 9.06 million US$, with 7 million US$ for the initial cost and 1.7 million US$ for the operational cost. The remaining cost components are relatively small for this case. This optimum cost is 34% less than the estimated actual cost (presented in Figure 4).

Because the pump power cost is higher than the pipe cost, one may assume that the optimum cost is not always the one with the smallest possible diameter; this is the case for all three pipeline projects. Notably, the best solution has a diameter larger than the minimum acceptable
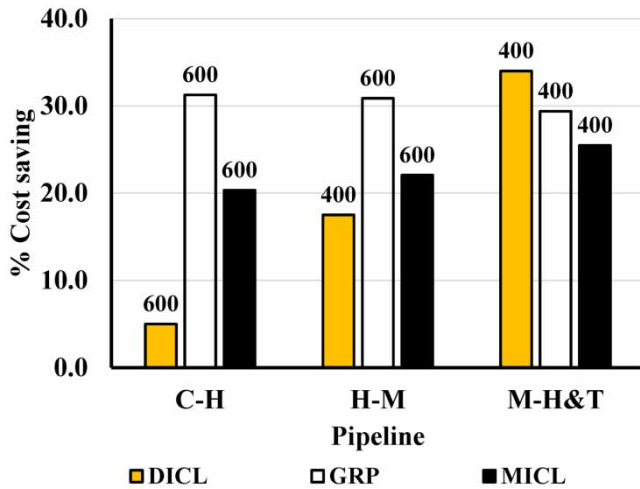
Figure 6 | Summary of the results for the three pipeline segments (with the diameter for the design shown above each bar in mm).

diameter and consequently has less head, which results in a lower operational cost. Thus, a larger pipe diameter is associated with a lower power cost. In these particular cases, large-dimeter pipes resulted in low overall project costs. Furthermore, pipe size reductions might decrease maintenance costs but may not offset the savings in the power cost. These findings are against the conventional design wisdom currently adopted in pipeline projects.

Figure 6 shows a summary of the results. Reduced costs can be achieved by optimizing the design with respect to the pipe size, pipe material, pressure rating, surge tank volume and surge tank inlet/outlet resistance. The first two have a much greater effect than the rest. For instance, for the C-H pipeline, the optimum design can save 31.3% if a GRP pipe with a diameter of 600 mm is used instead of a DICL pipe with a diameter of 400 mm, as implemented in the original design (see Figure 4). Similarly, approximately 30.9% can be saved if a GRP pipe with a diameter of 600 mm is used for the H-M pipeline instead of the DICL pipe with a diameter of 400 mm that was actually used. The largest saving is possible for the M-B&T pipeline when a DICL pipe with a diameter of 400 mm is used instead of the existing 300 mm DICL pipe. By inspecting the diameters of the original DICL pipes, the M-H&T pipeline has a diameter of 300 mm, while the diameters of the other two pipelines are both 400 mm (see Figure 3). Thus, it is

clear that savings are more pronounced for the DICL pipe when the diameter is smaller. Figure 6 shows that the GRP material is the most economical for two of the three pipelines, followed by the MICL material. The DICL material is the most economical for the 300 mm pipe only (M-H&T pipeline). Conventional designs could seek the optimum diameter without considering other factors, especially the pump power. The pipe pressure rating could also result in a less expensive system because it changes with the other pipe and surge tank parameters. Figure 6 clearly illustrates that no systematic or logical pattern can be identified regarding which material or pipe diameter could be used to achieve the optimum solution. It is thus advised not to use conventional design methods, and instead, it is recommended to consider all possible alternatives in the search space to achieve less expensive designs. When considering the lifecycle cost for a pipeline project, which includes the initial, maintenance and operational costs, it is assumed that no pipe material has any advantage over other materials and that all the solutions that do not violate the hydraulic constraints are considered equally good from a hydraulic perspective. Thus, it is advised not to adopt certain pipe materials and haphazardly neglect other materials because certain materials for certain projects may result in significantly lower lifecycle costs.

CONCLUSIONS

A comprehensive lifecycle cost procedure is established to compare pipeline project costs and select the most economical alternatives. The importance of the proposed approach comes from the fact that all the important cost components, namely, the initial cost, maintenance cost and operational cost, are accounted for when comparing alternative designs. Furthermore, average inflation rates are applied to estimate each future expenditure (e.g., maintenance costs and pump replacement costs); then, the investment is expressed in the present value using the average interest rate. The method compares alternatives after considering both steady and unsteady flow conditions for each alternative. A real-case project with medium-diameter pipelines

(300–600 mm) is used to investigate the possible savings of different alternative designs. It is found that the operational cost (pump energy) is high enough that its impact on the overall project cost is comparable to the effect of the initial cost of the pipe. Therefore, large-diameter pipes are generally found to be more economical because they provide low operational and overall pipeline costs. Because all the cost components are accounted for, different pipe materials are considered to be equally adequate. This study found that GRP pipes are the most economical, followed by MSCL pipes. This is especially true for pipes with a diameter greater than 300 mm. These findings suggest that no systematic pattern can be identified to conventionally find the least-expensive design for a pipeline. Thus, it is concluded that a thorough search needs to be conducted for such projects to find the absolute optimum solution, which includes all the cost components throughout the pipeline lifecycle. It is important to acknowledge the limitations of this study in the sense that these findings are based on the local costs of power, material and maintenance. For instance, if in another part of the world, the power cost, maintenance cost or material cost is very different from the one considered herein, the results will be different. Furthermore, as this study deals with medium pipe sizes and considers only three types of pipes – DICL, GRP and MICL pipes – other pipe materials and pipe sizes require further investigation to conclusively analyze the lifecycle cost.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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