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Model for optimal sectioning of hydrocarbon transportation pipelines by minimization of the expected economic losses

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ABSTRACT

Pipelines are the safest and most cost-effective alternative for transporting oil and refined products. Nevertheless, accidental losses of containment (LOCs) may occur, thus posing significant threats to people and the surrounding environment. These LOCs also lead to substantial economic losses due to remediation, commodity loss, emergency response, and property damage. The effects of an LOC might be mitigated by implementing proper maintenance plans and installing sectioning valves (i.e., blocking). The location and number of sectioning valves depend on the type of pipeline (underground or non-underground), the commodity being transported, the neighboring population density, and altimetry. Therefore, defining the optimal location and number of valves in a pipeline is a challenging decision that goes beyond the static distances suggested by recognized standards such as CSA Z662. In this paper, a model is proposed to determine the optimal number and location of sectioning valves, which minimize the expected economic losses in terms of the amount of volume spilled and the costs of remediation, emergency response efforts, repair, and commodity loss. The model is applied to a real oil pipeline with significant changes in altimetry. The results indicate a reduction between 10 and 18% of the expected economic losses compared with a static distance reported by CSA Z662.

1. Introduction

Pipelines are usually the preferred method to transport hazardous materials such as crude oil, refined oil products, highly volatile liquids, and biofuels mainly because they are considered the safest and most cost-effective alternative compared to train or ground transportation (Grigoriev and Grigorieva, 2009). Nevertheless, this mean of transportation is subject to different threats that may produce a loss of containment (LOC) that leads to human and environmental damage, and can trigger substantial economic losses regarding remediation, commodity loss, emergency response efforts, and property damage. This situation is a matter of concern because nearly 40% of the pipeline networks worldwide have reached their projected 20-year service lifetime (Azevedo, 2007). Although pipeline accident databases such as the Pipeline Hazardous Material Safety Administration (PHMSA), European Gas Pipeline Incident Data Group (EGIG), and CONCAWE reported lately that the number of LOCs have decreased with time (falling into failures rates from 1e-04 to 1e-03 incidents/km·year; see Aloqaily (2018)), there are still an important number of accidents with significant economic losses every year. For instance, according to PHMSA during 2009–2018, there was an average of 540 annual incidents of LOCs for onshore pipelines transporting hazardous liquids and gas. These accidents led to an average cost of 480 million dollars per year, which included property damage, commodity loss, emergency response efforts, and environmental remediation (Pipeline and Hazardous Materials Safety Administration, 2018).

Although the consequences of LOCs are not limited to economic ones. They also include possible impacts on environmental sustainability and the surrounding people (i.e., injuries or even deaths). The costs produced by a LOC are commonly used for risk-based decision-making processes Medina et al. (2012). Risk assessment is recognized as a valuable tool to support decisions seeking for a safe operation based on inspections and preventive/corrective maintenance (Cunha, 2016). Overall, a risk assessment is performed by estimating the probability of occurrence and the severity of the consequences that this event may produce (Shin et al., 2018). This assessment is then implemented in a risk management framework, willing to support decisions that reduce non-adequate risks. In this direction, decisions can focus on reducing the probability of failure or mitigating the severity of a given scenario. On the one hand, preventive decisions depend on the pipeline's current

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condition, as ascertained by periodic inspections (e.g., In-line (ILI) inspections); the predicted pipeline degradation; and the estimates of the mean time to failure or the failure probability. Some approaches that cover these decisions include Amaya-Gómez et al. (2019); Amaya-Gómez et al. (2016); Dundulis et al. (2016); Gomes and Beck (2014); Witek (2016); Zhang and Zhou (2014). Mitigating decisions consider scenarios in which an LOC has already takes place and the objective is to limit possible subsequent consequences. These decisions would depend on the spilled volume and the accident's potential impact on the surroundings in terms of the physical effects of overpressure, radiation, or toxic dispersion (Cunha, 2016; Shin et al., 2018). This paper concentrates on these latter decisions, and its scope is limited to the losses from the amount released and not extended to the possible upcoming events in the accident sequence.

One alternative to mitigate LOC in pipelines is the installation of blocking valves to isolate the affected section where the LOC takes place. If there is a rupture in the pipeline, the amount released would be limited by the quantity between two consecutive blocking valves. The problem, which is commonly known as the valve location problem, is to determine the number and location of these valves. If too many valves are implemented, the required capital cost and operational expenditure will increase excessively, but if too few valves are used, the potential spill would be boosted, which would increase the risk of major accidents (Grigoriev and Grigorieva, 2009). For liquid pipelines, these valves are usually located based on guidelines reported by the Code of Federal Regulation (49 CFR 195.260), the American Society of Mechanical Engineers (ASME B31.4 Section 434.15.2), or the Canadian Standard Association (CSA Z662). These guidelines suggest that blocking valves should be located near to high consequence areas like river crossings and public water reservoirs, near to mainline pump stations, and they should have predefined maximum separation distance between two consecutive valves (Research and Special Programs Administration, 2002). The maximum distances depend on how the pipeline is classified based on the location and fluid being transported. These distances aim to facilitate operational controls and repairs, and they seek to reduce the duration of an LOC as well. Some examples of maximum separation distances include 7.5 miles (12 km) for highly volatile liquids (HLV) in high consequences areas (HCA), 10 miles (16 km) for non-HVL in HCA, and 20 miles (32.2 km) for pipelines transporting non-HVL in non-HCA (Enterprise Products, 2012). CSA Z662 considers a valve spacing for liquid transmission lines of 15 km for most class locations in high vapor pressure pipelines (Canadian Standard Association, 2011). These references define guidelines for locating valves depending on the type of pipeline, but there is no specific cross-country spacing requirement (Michael Baker Jr, Inc, 2008), and the pipeline operation and altimetry profile are not considered. Therefore, the problem of determining the number and location of blocking valves is not limited by a static approach, and optimization strategies that deal with integral designs must be considered (Bodlaender et al., 2007).

In this regard, some research has been done up to this moment. Fontecha et al. (2016) proposed an approach to determine the number and location of sectioning valves to minimize environmental risk and guarantee a tolerable individual risk. Weir et al. (2006) proposed an approach to optimize valve locations by applying consequence-reduction strategies, strategic valve positioning, and other operability tactics. Grigoriev and Grigorieva (2009) worked in the location of valves to minimize the environmental damage of a crude oil spill. Accordingly, Rout (2012) presented a solution for optimal valve location in interconnected and isolated systems via the generation of interactive scenarios and hydraulic modeling. In the same line of research, Weir and Li (2008) described an approach to locate valves that accounts for the protection of water bodies, the potential of spilled volume reduction in high consequence areas, and a threshold of fixed spilled volume. These authors proposed some improvements to the model of intelligent valve location that include setting up the space between valves in high vapor pressure pipelines and the application of value evaluation to the positioning process, which may or may not contain high consequence areas (Li and Weir, 2012). Finally, Restrepo et al. (2009) examined the causes and economic consequences of accidents involving hazardous liquid pipelines using historical data from the US Department of Transportation.

This paper aims to integrate the loss evaluation and the location of sectioning valves looking for a robust and feasible model that supports the optimal design and planning of liquid hydrocarbon pipelines. The model described here employs an economic proxy to quantify the consequences of an LOC. This proxy is directly related to the potential spilled volume. The model provides some insight into how different accidents features are associated with consequence measures and how these features represent important inputs for risk management of transportation systems. Overall, costs are often used to classify the severity of pipeline failures (Restrepo et al., 2009), and also have been used for the valve location problem. However, little has been published on attempts to minimize the expected economic losses from LOC accidents. The proposed approach incorporates the altimetry profiles of the pipeline to calculate the potential spilled volume considering the topographical particularities. Except from Fontecha et al. (2016), who reported two case studies with considerable changes in the altimetry profile, the use of the area type and altimetry profile to estimate the expected economic losses based on the potential spilled volume is unusual.

The article is organized as follows. Section 2 describes the valve location problem. Section 3 provides the proposed methodology, divided into two stages: (i) a framework to calculate the cost parameters is presented, and (ii) an optimization approach is defined. Section 4 shows the application of the methodology to a real case study. Section 5 concludes the work and outlines future research guidelines.

2. Description of the valve location problem

2.1. Problem overview

An LOC represents a spillage of the fluid being transported in the pipeline, which initially would affect the neighboring population and environment due to the dispersion of a toxic compound. The consequences of this spillage could be aggravated because of the presence of an ignition source (e.g., fire or an explosion) under certain conditions (Bubbico et al., 2016). In either case, this spillage triggers economic losses that can be determined by commodity loss and the costs of maintenance/repair of the pipeline, environmental remediation, and emergency response efforts. The commodity loss refers to the lost product that was evaporated, filtrated, or precipitated and could not be recovered. The maintenance/repair costs include unplanned shutdowns, inspections of the affected location, segment replacements, and excavations. The remediation costs include those of assisting affected people and recovering the environmental damage (e.g., aquatic, soil) caused by the spillage. Finally, the emergency response costs involve controlling the spill and mitigating its foreseen consequences. Overall, the aforementioned costs would depend on the particularities of the pipeline location, but they are directly related to the potential amount of volume spilled ($\tilde{V}$) (Prendergast and Gschwend, 2014).

This volume has two main contributions: (i) dynamic volume ($\dot{V}$) and (ii) static volume (V). The dynamic volume corresponds to the flow before valve closure; it is often assumed as constant by the worst-case scenario and it is calculated as the product between the maximum flow rate and the maximum closure time of the valves (Bidmus et al., 2013; Mohitpour et al., 2004). The static volume is related to the hydrostatic charges after valve closure, which are associated with the (i) remaining volume between two consecutive valves and (ii) the volume that is released because of hydrostatic head pressure (Fontecha et al., 2016). The approach proposed in this paper aims to integrate the expected economic losses of LOC accidents using estimations of the effects of the

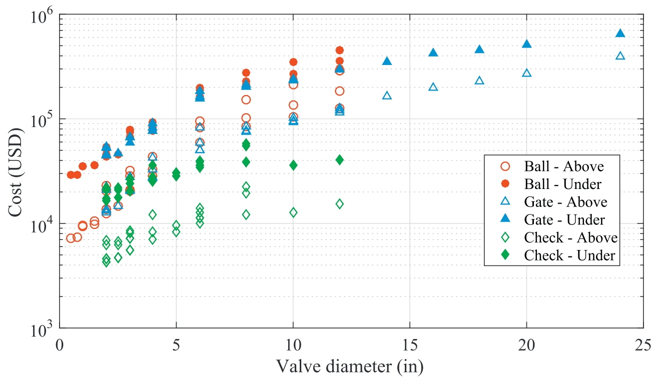

Fig. 1. Costs in 2017 USD of underground and aboveground valves of various sizes.

potential spilled volume. The valve location problem then relies on estimating the number of valves and their optimal location along the pipeline to minimize the underlying consequences in case of an LOC (Grigoriev and Grigorieva, 2009). This problem has two principal components: one associated with the economic losses that an LOC may trigger, and another with the cost of the equipment that is required to limit the amount of volume released.

However, the valve location problem is not straightforward, considering that the costs of sectioning depend, for instance, on the pipeline's diameter and location (i.e., underground or aboveground), as shown in Fig. 1. This figure depicts the total costs (i.e., capital expenditures and the operational costs) in 2017 USD of underground and aboveground valves of different sizes. These costs were estimated based on material and equipment quotations from the hydrocarbon transportation sector between 2012 and 2017. The obtained costs present a direct proportionality between valve size and average cost. Additionally, this figure indicates that underground valves are considerably more expensive than aboveground valves for three different types of valves: ball, gate, and check.

2.2. Problem description based on graph theory

A pipeline comprises a series of n joined segments. These segments can be assumed to have similar lengths. The valve location problem aims to identify the location and number of blocking valves at the beginning or end of these segments, to minimize the expected losses. These losses include the potential volume released from a LOC between two consecutive valves, and the capital and operational costs of the equipment. This problem can be described by a directed graph in which the different "paths" (or combinations) of valves are compared. Formally, consider a directed graph $\mathcal{G}(\mathcal{V}, \mathcal{A})$ comprising a collection of points or nodes $\mathcal{V}$ and directional arcs $\mathcal{A}$ that connect the nodes. A node $i \in \mathcal{V}$ exists if it is possible to place a valve over it (i.e., there are $n+1$ nodes from 0 to n). Considering that a pipeline is a series system with marked beginning and ending distribution stations, the initial and final segments have two fixed valves at the nodes 0 and n. Pipelines also can have valves at the intermediate nodes (Fig. 2). If $\mathcal{V}_f$ denotes the location of the final valves, then it follows that $\{0, n\} \in \mathcal{V}_f$. Regarding the arcs $\mathcal{A}$ of the directed graph, they represent the potential spilled volume if a failure occurs between two nodes. These arcs are restricted to having a linear distance between consecutive valves that is less than the maximum distance recommended in CSA Z662 of 15 km (Canadian Standard Association, 2011). Formally, the arcs are defined as $\mathcal{A} = \{(i, j)|i, j \in \mathcal{V}, i < j, i \neq j\}$ such that $\|j - i\|_x \leq 15\text{km}$, where $\|\cdot\|_x$ is the distance in the longitudinal direction.

Define a route as a path from node 0 to n flowing along through the network where each node in the route is the location of a valve. Fig. 3 illustrates a route (valve configuration) for a pipeline with 6 nodes and 4 valves. In this example, $\mathcal{V}_f = \{0,2,3,5\}$, the route is $\{(0,2), (2,3), (3,5)\}$, and the distance between consecutive valves are less or equal than 15 km. The objective is to find the route that minimizes the expected value of the economic losses related to the potential spilled volume.

The assumptions and conditions of the problem are summarized as follows:

1. The distance between two consecutive nodes is discrete (i.e., the pipeline is divided into equidistant sections).
2. The parametric information of each node (e.g., abscissa, height, and pipe diameter) is deterministic and known.
3. The parametric arc contributions (distance and spilled volume) are deterministic and known.
4. To calculate the contributions of each arc, an LOC is assumed to be complete and to occur in only one node at a time (i.e., only a total rupture is considered).
5. After an LOC takes place, the affected section is isolated by closing its nearest valves.
6. All the nodes in a given section are equally vulnerable to an LOC, so they have the same failure probability.

The isolation from the affected pipe segment implies that the main contribution of the spill volume is attributed to the hydrostatic charge. Finally, the equally vulnerable nodes indicate that unforeseen LOCs are not contemplated in the model (Fontecha et al., 2016).

3. Valve location framework

3.1. Methodology overview

The objective of the proposed model is to find the optimal location and number of valves that minimize the expected economic losses. Therefore, a parameter calculation framework is developed to include the economic losses in the optimization model. This calculation uses the potential spill volume to estimate the expected economic losses, as shown in Fig. 4. Based on the pipeline topography (i.e., altimetry), operation conditions, and design guidelines, the spill volume is estimated. At this point, a shortest path optimization is implemented to select the optimal sectioning alternative based on the spill volume, its estimated economic losses, and the capital costs of equipment from the sectioning alternatives following the approach of Lozano and Medaglia (2013). This approach can prune non-optimal paths, assuring optimality. In what follows, the framework and the optimization model are described in more detail.

3.2. Potential spill volume calculation

As discussed in Section 2.1, the total spill volume is composed of the dynamic and static volumes, which depend on the closure time of the

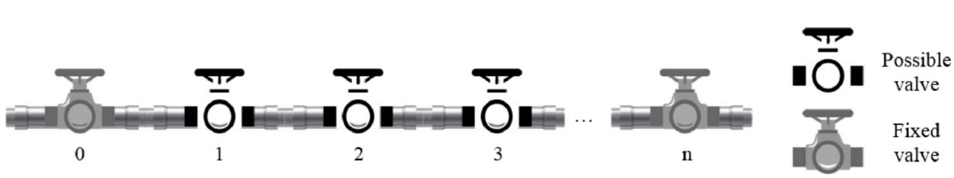

Fig. 2. Graph $\mathcal{G}(\mathcal{V}, \mathcal{A})$ representing a pipeline with n segments.

Fig. 3. A feasible route for a pipeline with 6 nodes and 4 valves.

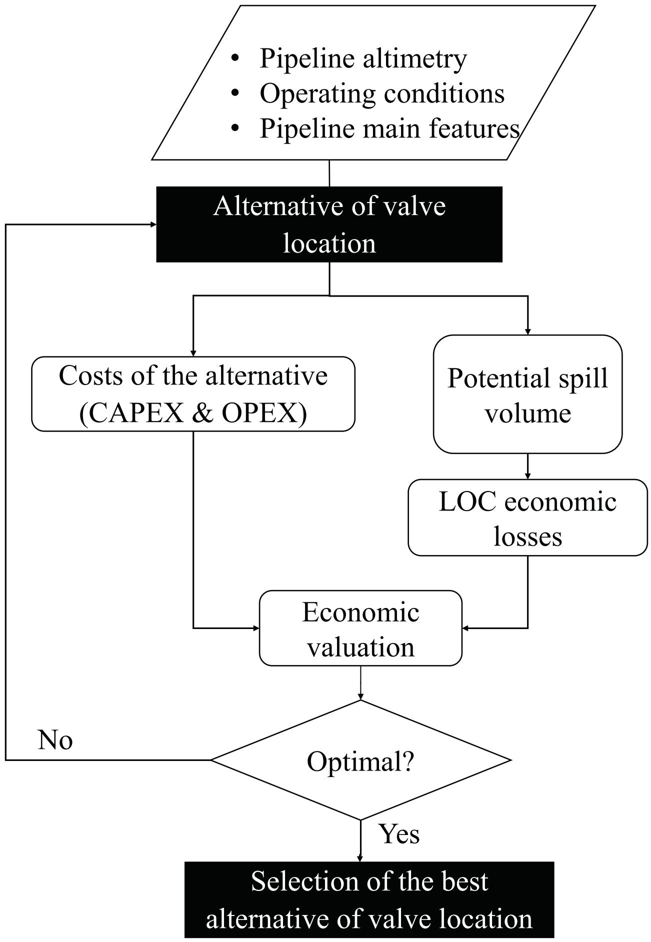

Fig. 4. Parameter calculation framework and optimization.

nearest sectioning valves and the hydrostatic head of the pipe section. For this work, the time to close the valves is assumed constant, which leads to an almost constant dynamic volume. A more robust approximation would consider a random variable of this closure time, as well as an additional time when the failure is determined. However, these alternatives are outside the scope of the present work. Hence, the dynamic volume is initially omitted for the model calculation. For the static spilled volume, the approximation discussed by Fontecha et al. (2016) is used, which considered the worst-case scenario for LOC accidents generated in all segments along the pipeline. This approach estimates the static volume as a liquid spill on consecutive vertical tanks following the remarks of Crowl and Louvar (2001). This model assumes that the segments of the pipeline contributing to the static volume can be added to obtain an equivalent liquid column relying on the failure. This alternative was considered by Fontecha et al. (2016) aiming to reduce the complexity of the calculation.

After the potential volume of each node V_k is calculated, the expected value of the static volume for each arc (i, j) follows Eq. (1). For each arc $(i, j) \in \mathscr{A}$, we consider a complete LOC in all nodes $k \in \mathscr{V}: i \leq k < j$. According to the assumption that all sections have an equal probability of failure, we use the average V_k as the expected value and assign it to V_{ij}.

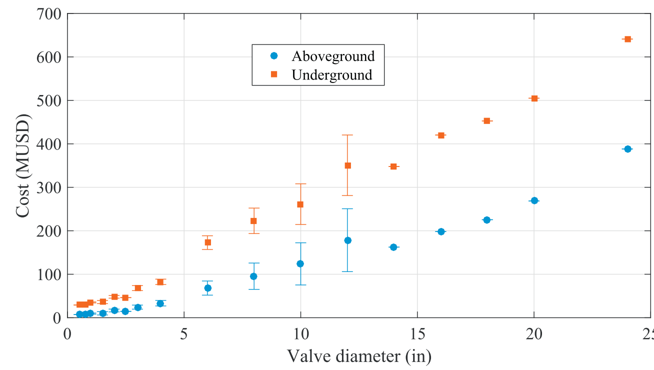

Fig. 5. Average cost in 2017 USD of underground and aboveground valves.[1]

$$V_{ij} = \frac{\sum_{k=i}^{j} V_k}{j - i}, \quad \forall\ (i, j) \in \mathscr{A} \tag{1}$$

If the failure probability is not equally assumed, then Eq. (1) would change based on the definition of discrete expected value using the equivalent failure probability of each node, i.e., $V_{ij} = \sum_{k=i}^{j} (V_k \cdot P_k) / \sum_{k=i}^{j} P_k$, where P_k stands for the failure probability of the k^{th}-node.

3.3. Economic proxy calculation

Hazardous liquid accidents can trigger consequences that include deaths, injuries, environmental damage, and severe economic losses (Restrepo et al., 2009). This work focuses exclusively on the expected economic losses and proposes an economic proxy calculation that considers the cost of the sectioning alternative. This economic proxy also aims to quantify how different accident characteristics affect the economic losses depending on the spilled volume. The economic proxy will be described in more detail in the following sections.

3.3.1. Cost of sectioning alternative

The cost of implementing the sectioning alternative includes capital expenditures (CAPEX) and operating expenses (OPEX). CAPEX costs are composed of the purchase costs, i.e., valve DDP, nationalization, and in place taxes. OPEX costs are determined by the present value of operation and maintenance costs of valves during their lifetime, which, for this work, is assumed to be 20 years; the corresponding discount rate is taken as 11.1% annual equivalent (AE) following recommendations from the hydrocarbon transportation market. OPEX costs are composed of (i) Installation costs for underground and non-underground valves including overhead, contingencies, and profit fees. These installation costs also include bunker construction and supplies for underground valves. (ii) Other direct costs such as commissioning, startup, and stabilization; (iii) indirect costs such as engineering, management, and insurance; and (iv) contingency costs for systemic and specific risks associated with the project.

Fig. 5 shows some of the estimates for the average total cost (CAPEX + OPEX) of underground and non-underground valves of various sizes in 2017 USD. This figure also includes the 95% confidence intervals for these means based on the sample standard deviation, the number of the sample, and the critical value for the t-distribution. Note

[1] Where MUSD stands for thousands of U.S. Dollars.

that after 14 inches, the confidence intervals are not included because only gate valves were reported for these diameters (see Fig. 1). As mentioned before, underground valves have a considerably higher cost than non-underground valves. We consider the average total costs for ball and gate valves, which are commonly used in the transportation of liquid hydrocarbons. The inputs of the model for the cost of implementing the sectioning alternative depend on the size of the valve and whether it is an underground or aboveground configuration.

3.3.2. Cost of expected economic losses

The economic losses due to an LOC in a pipeline may depend on different scenarios such as the environment (e.g., aquatic), type of pipeline, altimetry, transported commodity, and the neighboring population that is affected. Despite that these scenarios have clear differences, an overall cost can be compared based on the amount of spilled volume. In this direction, the information obtained from the return of experience from past events can be used in advance from the reports of accidental databases. From the available databases around the world, the PHMSA provides detailed information for these losses. There are other databases, such as MHIDAS (Major Hazard Incident Data Service) and TSB (Transportation Safety Board of Canada), that also include some economic indicators (SRD, Safety and Reliability Directorate, 2006; Transportation Safety Board of Canada, 2016), but these indicators are not as detailed as those reported by PHMSA. Therefore, for this paper, the records of accidents in hazardous liquids transportation pipelines from the PHMSA database are used to estimate the economic losses of LOC events.

The PHMSA database reports the total estimated cost of the accident, which is composed of the following individual costs: (i) the cost of the public and non-operator's private property damage; (ii) the cost of the commodity lost; (iii) the cost of the operator's property damage and repairs; (iv) the cost of the operator's emergency response; (v) the cost of the operator's environmental remediation; and (vi) other costs.[2] Some basic statistics from the PHMSA records that meet the criteria to be classified as significant by the PHMSA database[3] are depicted in Table 1, based on their total costs in 2016 USD and volume spilled for Crude Oil (393 records) and Refined Products (269 records). This table illustrates how accidental events represented a large spill volume with a mean value of 457 barrels for crude oil and 277 for refined products. Regarding the costs, this table suggests that 10% of the accidents reported economic consequences lower than US$85,000, but these costs rose to US$4.5 million for crude oil and US$1.2 million on average. The maximum loss was reported in the Kalamazoo River event (Michigan, USA) in July 2010, where a spill of 20,082 barrels represented costs of US$913 million (Pipeline and Hazardous Materials Safety Administration, 2017).

3.3.3. Feature selection to describe economic losses

To estimate the economic losses, we initially looked for a group of characteristics that allow the generation of configurations based on the consequences of an accident (measured in different types of sub costs). These characteristics should be related to the surroundings of the accident that are known in advance. In this regard, PHMSA contains information about accidents involving hazardous liquids pipelines, which include costs due to property damage facilities, commodity lost, facility repair and replacement, and environmental cleanup and damage (Pipeline and Hazardous Materials Safety Administration, 2016). These variables were compared in terms of their correlation with the spilled volume and total costs, and those with higher relevance have been selected and depicted in Table 2. Some features of each variable were excluded because they may be considered irrelevant or too specific for the model. In addition to the PHMSA variables, High Consequence Areas (HCA) were considered based on the definition of CFR 49, i.e., specific locations and areas where a release could have the most significant adverse consequences. Based on the aforementioned, the model considers the estimation of economic losses for each of the six types of costs (or sub cost) using the volume as an explanatory variable. These costs are determined for each configuration based on the (i) location of the accident, (ii) commodity released, and (iii) the HCAs, obtaining 12 configurations.

3.3.4. Regression analysis per sub cost

The behavior of each sub cost for the 12 different configurations is examined using the historical data of accidents in the PHMSA database seeking for the functional form of the volume in the cost estimation. Although the data for all types of cost present some extreme values, it was found that three sub costs have relative dominance over the three remaining sub costs. These are the costs of the operator's property damage and repairs *OperPropDamage*, the cost of the operator's emergency response *EmergResp*, and the cost of the operator's environmental remediation *EnvirRemed*. Based on the previous information, the linear functional form given by Eq. (2) is evaluated. The coefficient β_1^l estimates the contributions in USD of every additional spilled barrel, whereas the coefficient of β_0^l is associated with a fixed cost of the accident even if there is not a spill volume.

$$C_{ijl} = \beta_0^l + \beta_1^l V_{ij} + \varepsilon_{ijl} \tag{2}$$

In this equation, l represents each of the 6 sub costs; therefore, linear regression models were executed for each sub cost and configuration. The results for the coefficients for the 6 sub costs in all 12 configurations are shown in Tables 3 and 4. The dominant sub costs mentioned above are marked in the coefficients shown in these tables. Models that contain variables with p-value ≥ 0.1 were not considered in the calculations. From these configurations, note that some cases do not include the fixed positive contribution.

3.4. Optimization model

The economic proxy function C_{ijl} was calculated using Eq. (3) for each arc and sub cost, i.e., $\forall\ (i, j) \in \mathscr{A}$, $l \in \mathscr{E}$, where $\mathscr{E}$ is the set of 6 sub costs (see Section 3.3). This equation allows the model to select for all successor $j \in \mathscr{V}$ and node $i \in \mathscr{V}$ the estimated economic proxy associated with the potential spill volume V_{ij} (see Section 3.2).

$$C_{ijl} = f_l(V_{ij}, x_{ij}, P_{ij}), \quad (i, j) \in \mathscr{A} \tag{3}$$

Here, $f_l(V_{ij}, x_{ij}, P_{ij})$ denotes the expected cost for each $l \in \mathscr{E}$, and P_{ij} denotes the failure probability of the arc (i, j), which can be calculated based on the failure probability of the nodes therein. Let x_{ij} be a binary variable that takes 1 if valves are located in $i, j \in \mathscr{V}$, and 0 otherwise; thus, the optimization function is defined as follows:

$$\min_{x_{ij}} C_T = \sum_{l \in \mathscr{E}} f_l(V_{ij}, x_{ij}, P_{ij} | LOC) + C_{SA} \tag{4}$$

Eq. (4) minimizes the total costs, namely the cost of expected economic losses and the cost of a sectioning alternative (SA) in a pipeline according to a valve configuration. The term in the summation defines the expected value of economic losses as an additive function of all sub costs for a configuration given an LOC. Therefore, the failure probability $P_{i,j}$ is assumed as 1 for every $(i, j) \in \mathscr{A}$; this expected cost depends on the parameters of a given arc. The cost of the sectioning alternative is defined as the sum of the cost of the capital expenditures and the operating expenses according to a given configuration as follows:

[2] For simplicity, these sub costs are denoted as (i) *PubPropDamage*, (ii) *CommodLost*, (iii) *OperPropDamage*, (iv) *EmergResp*, (v) *EnvirRemed*, and (vi) *Other*.

[3] An event that triggers a fatality, injury, fire, explosion, total property damages greater or equal to 50,000 USD or a spill greater or equal to 50 barrels of liquid spilled (Pipeline and Hazardous Materials Safety Administration, 2016).

Table 1
Values for crude oil and refined products spills (Pipeline and Hazardous Materials Safety Administration, 2016).

Measurement[a]	Spilled volume-Crude oil (barrels)	Total cost-Crude Oil (USD[b])	Spilled volume-Refined products (barrels)	Total cost- Refined products (USD[b])
P10	0.24	$ 26,698	0.10	$ 82,891
P50	70.00	$ 205,519	23.00	$ 315,421
P90	718.00	$ 2,778,114	650.00	$ 2,141,037
Mean	457.15	$ 4,572,216	277.28	$ 1,259,892
Maximum	20,600.00	$ 912,771,200	9000.00	$ 38,056,632

[a] P10: 10% percentile, P50: 50% percentile, P90: 90% percentile.
[b] 2016 USD.

Table 2
Variables to be included in models (Pipeline and Hazardous Materials Safety Administration, 2016; US Federal Register, 2014)

Field Name	Variable type-units	Description	Abbreviation
Estimated volume unintentional released	Continuous - Barrels	1803 records distributed as P10 = 0.2, P50 = 2, and P90 = 145	*Vol*
Location of accident[a]	Categorical	1803 records distributed as: Non Underground (65%) and Underground (35%)	*NonUndgr* and *Undgr*
Commodity released	Categorical	1803 records distributed as: Refined products (42%) and Crude Oil (58%)	*Refn* and *CrOil*
High Consequence Area (HCA)	Categorical	1803 records distributed as: High Population Area[b] (25%), Other Populated Area[c] (15%), and Non HCA (60%)	*HighPop*, *OtherPop*, and *NonHCA*

[a] Only onshore locations were considered.
[b] HighPop: Urbanized area with ≥50,000 people and a population density of ≥1000 people per square mile.
[c] OtherPop: Area with concentrated population, e.g., an incorporated or unincorporated city, town, village.

$$C_{SA} = C_{Capex} + C_{Opex} \tag{5}$$

The constraints of the model are shown in Eq. (6). These constrains evaluate the flow balance in each node in order to ensure that paths flow in the network from 1 to $(n-1)$. There are two exceptions: nodes 0 and n, which represent the source and sink. Both nodes have operating valves placed over them.

$$\sum_{(i,j)\in\mathscr{A}} x_{ij} - \sum_{(j,i)\in\mathscr{A}} x_{ji} = \begin{cases} 1, & i = 0 \\ 0, & \forall\, i \in \{1,\ldots,(n-1)\} \\ -1, & i = n. \end{cases} \tag{6}$$

Finally, the set of constraints in Eq. (7) indicates that the integrality of the variables is relaxed to reduce the complexity of the optimization.

$$x_{ij} \geq 0, \quad \forall\,(i,j) \in \mathscr{A} \tag{7}$$

Modeling the problem in a network allows this relaxation, which ensures that the solution of the variables is an integer (binary) (Ahuja et al., 1993). In this case, the expected cost of consequences decreases when more valves are placed in the pipeline, which is consistent with a reduction in the spilled volume in points between valves. The cost of the sectioning alternative increases linearly as more valves are placed in the pipeline. As a consequence, a trade-off between these costs must be found such that the total cost is minimized as depicted in Fig. 6, where a linear capital cost is considered based on the number of valves while assuming a constant valve price to identify a path with 22 valves.

4. Results and discussion

4.1. Case study

The model was tested on a real case study with a diameter varying from 10 to 12 inches. This pipeline transports liquid hydrocarbons through a distance of 110 km in highlands that are between 124 and 2600 m above sea level. Further details about this case study could not be provided due to confidential agreements. A hypothetical underground configuration that transports crude oil in a highly populated area is considered.

4.2. Static spill volume and valve location alternatives

Fig. 7 shows the profile of altimetry and the calculated potential spill volume along the pipeline using the description in Section 3.2. The highest slope changes are located between 80 and 100 km and represent the lowest potential spill volume. Note that this figure indicates that the highest spill volumes are located at the preceding segments of the slope differences, near 70–80 km and 20–40 km. This spill profile provides an idea of which areas are particularly susceptible to significant consequences in an LOC event and should thus be given special attention when locating blocking vales as a mitigation tool.

For each distance, two alternatives were considered: (i) positioning valves along the pipeline according to the CSA Z662 norm, which states that the distance between two consecutive valves should not exceed 15 km, and (ii) positioning valves according to the sectioning alternative obtained by our model. The optimization model was tested while considering that valves could be placed with minimum distances of 1000 m, 500 m, 300 m, 200 m, and 100 m.

4.3. Economic proxy and optimization results

A comparison of the expected costs based on economic losses, sectioning, and the corresponding total costs between the CSA criterion and the proposed model is depicted in Fig. 8a. This figure shows that the proposed model reduces the expected economic losses based on the potential spill volume for all testing alternatives. This figure also illustrates that the sectioning cost is higher for the proposed model, which is consistent with the use of a higher number of valves to achieve the minimum total cost. However, this additional cost in the sectioning alternative is almost negligible in comparison to the reduction of the economic losses using the proposed approach, as it can be noticed in the total costs. This result remarks the need to contemplate further tools besides the use of the norm to minimize the total cost of the whole system. The lower total cost is obtained when the distance between valves is 100 m, which corresponds to the lowest number of valves for all tested distances (9 valves).

The results depicted in Fig. 8a also indicate that for greater segments or distance between nodes, the expected total cost increases as well, and the difference between the alternatives is more pronounced. This result can be explained by the fact that greater distances between nodes would include critical points based on the potential spill volume, which in turn, could aggravate the economic losses of the six costs considered in this paper. Thus, it would be convenient to find a suitable

Table 3
Values for β_0^l (USD) in regression models.

		CrOil	CrOil	CrOil	CrOil	CrOil	CrOil	Refn	Refn	Refn	Refn	Refn	Refn
		Undgr	Undgr	Undgr	NonUndgr	NonUndgr	NonUndgr	Undgr	Undgr	Undgr	NonUndgr	NonUndgr	NonUndgr
		HighPop	OtherPop	NonHCA	HighPop	OtherPop	NonHCA	HighPop	OtherPop	NonHCA	HighPop	OtherPop	NonHCA
Sub cost	1.PubPropDamage			13,226.5*		25.9					127.0		
	2.CommodLost		5570.6*							6142.4*			303.6*
	3.OperPropDamage		451,981.8*		29,785.0					57,557.0***	34828.0	78,560.0	18,719.0
	4.EmergResp			130,678.7**			16,135.6				13,620.3	11,809.7	21,159.6***
	5.EnvirRemed			85,933.3**			16,826.3				14,720.3	16,257.6	
	6.Other			23,304		668.1	1412.0	23,910.0			1127.0	3201.8	271.2

$^{***}p - value < 0.01$, $^{**}\ p - value < 0.05$, $^{*}\ p - value < 0.1$.

Table 4
Values for β_1^l (USD/bbls) in regression models.

		CrOil	CrOil	CrOil	CrOil	CrOil	CrOil	Refn	Refn	Refn	Refn	Refn	Refn
		Undgr	Undgr	Undgr	NonUndgr	NonUndgr	NonUndgr	Undgr	Undgr	Undgr	NonUndgr	NonUndgr	NonUndgr
		HighPop	OtherPop	NonHCA	HighPop	OtherPop	NonHCA	HighPop	OtherPop	NonHCA	HighPop	OtherPop	NonHCA
Sub cost	1.PubPropDamage	1552.6***	1293.9***	13.2**	237.6**	0.2	21.4	394.4***	337.1	16.1**	4.0	0	29.4**
	2.CommodLost	26.3***	8.0***	63.0***	309.8***	67.2***	34.5***	61.6***	119.2***	61.2***	48.2***	32.7***	52.2***
	3.OperPropDamage	524.7***	182.3*	30.7*	505.7	897.4***	264.5***	1057.9**	1798.5***	27.6**	17.2	−84.3	216.5
	4.EmergResp	6814.7***	8684.9***	255.0***	2813.7***	529.1***	22.9***	3449.0***	953.4***	825.5***	119.7***	103.7***	375.2***
	5.EnvirRemed	3099.9***	29,439.2***	559.9***	1561.2***	550.8***	42.0***	1934.5***	436.3	1163.2***	562.6***	93.9***	1446.4***
	6.Other	1171.2***	249.1*	4.85	1780.3***	−1.4	3.1	144.4	0	380.3	18.8	12.7*	−2.0

$^{***}p - value < 0.01$, $^{**}\ p - value < 0.05$, $^{*}\ p - value < 0.1$.

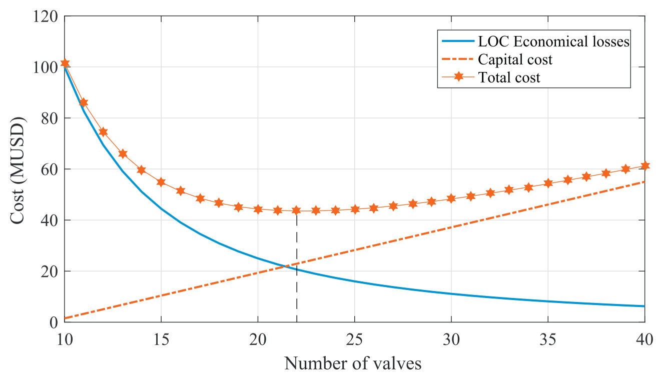

Fig. 6. Total costs of the valve location problem - A scheme.

distance between nodes such that the consequences for almost every critical point are considered in the model; however, the next problem would be the excessive computational capacity to run the model. Following the results depicted in Fig. 8b for all 12 configurations, a distance between nodes of 100 m tends to stabilize the cost reduction obtained via the model; therefore, this distance was implemented for this case study.

The results for the configuration and valve location for 100 m between valves for both alternatives are summarized in Table 5 and Fig. 9. The results show that the value for the reduction in total cost is approximately 17.79% for the tested configuration despite that the proposed model use 4 additional valves along the pipeline. It should be noted that, although the optimization time increases with the number of arcs, the bulk of the computation time relies on the generating of parameters for the network, which is approximately 10 times greater the optimization time.

Table 5
Results for *CrOil/Undgr/HighPop* configuration with a distance between nodes of 100 m.

Model parameters and performance	Value
%Cost reduction	17.79%
Optimization time	4851.46 s
Total nodes	1090
Total arcs	151,146

To illustrate this cost reduction, the distribution of the total cost given an LOC along the pipeline from the two alternatives are shown in Fig. 10. This figure also depicts the 10, 50, and 90 percentiles for each distribution. The results illustrate that the CSA valve position criterion tends to produce greater costs than the proposed model, which tends to reduce extreme values of the expected cost of consequences. P90 indicates a significant reduction in the expected cost of consequences, estimating that 90% of all LOC accidents would be less than USD 17.94 million for the proposed approach whereas lower than USD 26.75 million according to the CSA alternative.

In most cases, the estimation of the cost of consequences for LOC accidents is considerably lower for pipelines transporting refined products than for those transporting crude oil. As a result, when the cost of consequences is similar to the cost of the sectioning alternative, like in the case of refined products, the number of valves placed by the model is less affected by the distance between the valves. Regarding the location of the valves, the model locates a higher number in areas with high expected costs (between 70 and 80 km). Table 6 presents the results obtained with the model for the 12 configurations combining the variables for type of area, commodity transported, and type of HCA. In some configurations, the model relocates the minimum number of

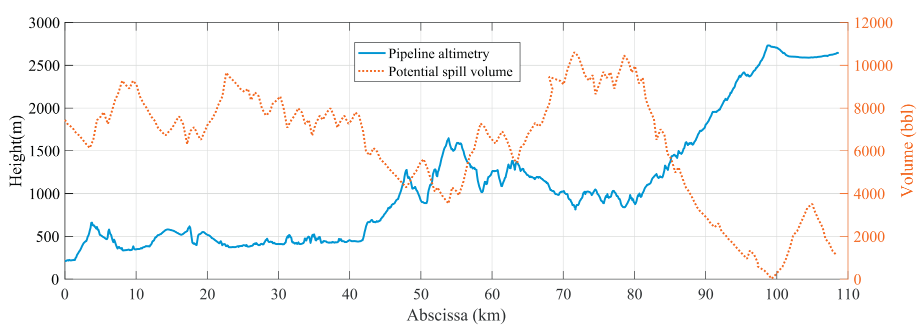

Fig. 7. Static volume in case-study.

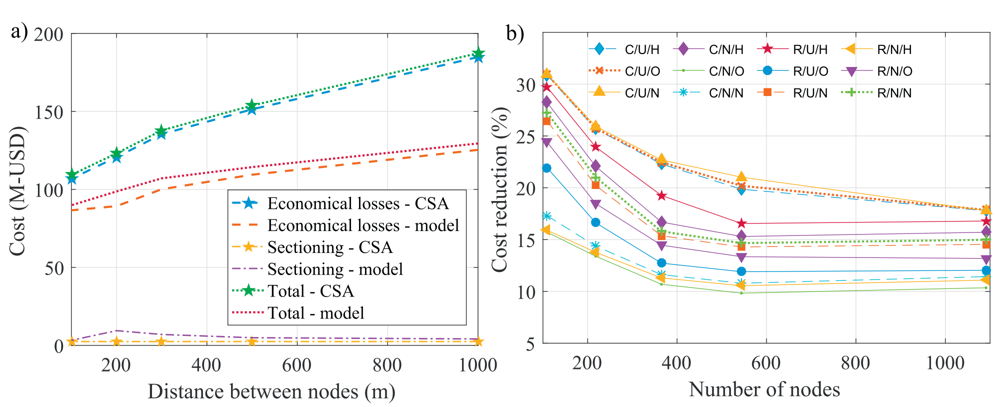

Fig. 8. Optimization results for different distance between nodes. C: Crude Oil, R: Refined products/N: Non Underground, U:Underground/H: High Population Area, O: Other Populated Area, N: Non HCA.

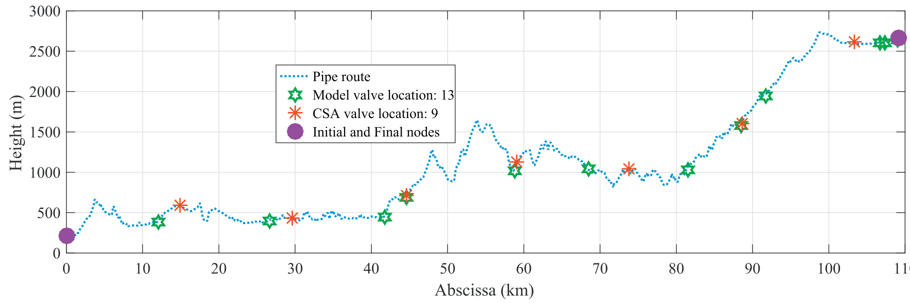

Fig. 9. Valve location for tested configuration: underground pipeline that transports crude oil in a high population area. Distance between nodes: 100 m.

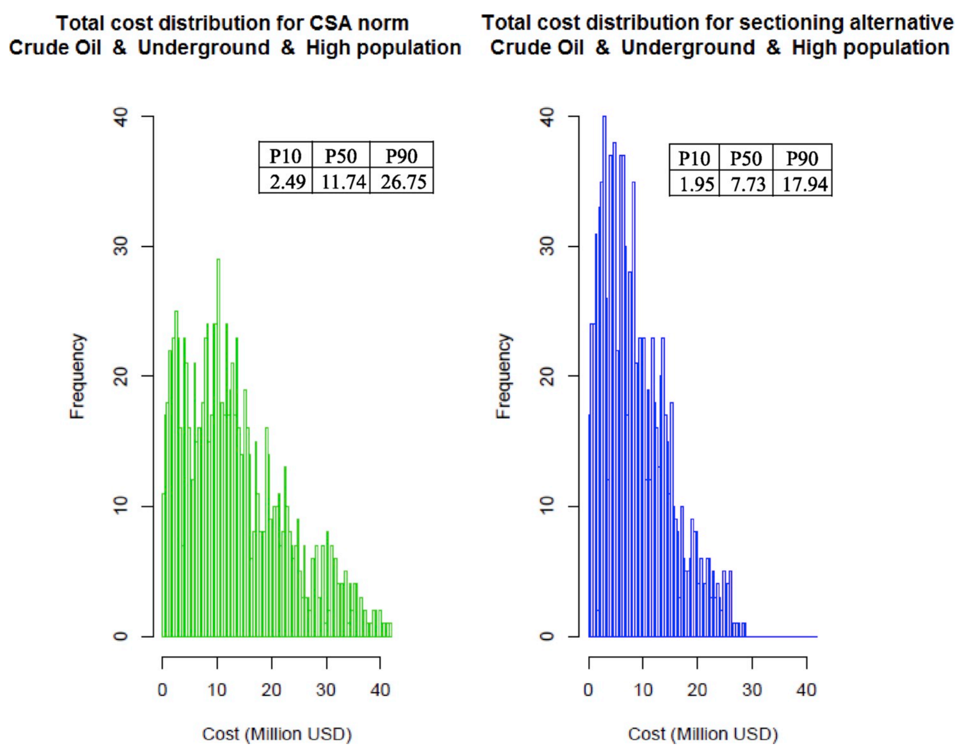

Fig. 10. Cost distribution for tested configuration. Distance between nodes: 100 m.

Table 6
Results for sectioning alternatives for 12 configurations. Distance between nodes: 100 m.

Configuration			Number of valves	Total Cost (M-USD)	Cost reduction
Product	Design	Area			
CrOil	Undgr	HighPop	13	89.81	17.79%
CrOil	Undgr	OtherPop	15	270.34	17.79%
CrOil	Undgr	NonHCA	9	10.53	10.35%
CrOil	NonUndgr	HighPop	13	45.54	17.86%
CrOil	NonUndgr	OtherPop	12	14.94	15.71%
CrOil	NonUndgr	NonHCA	9	3.88	11.43%
Refn	Undgr	HighPop	13	48.5	16.79%
Refn	Undgr	OtherPop	12	21.95	14.54%
Refn	Undgr	NonHCA	11	16.92	13.18%
Refn	NonUndgr	HighPop	9	6.43	12.04%
Refn	NonUndgr	OtherPop	9	3.01	11.09%
Refn	NonUndgr	NonHCA	12	14.24	14.98%

valves to minimize the total expected cost, whereas in other cases, a small number of valves was implemented to achieve the minimum expected cost. The range of the cost reduction was from 10.35% for the configuration transporting crude oil through an underground pipeline in a non-HCA to 17.86% for the one transporting crude oil through a non-underground pipeline in a high-population area.

The reader should bear in mind that this work focuses on an optimization approach based on the worst consequences exclusively, and the pipeline's spatial reliability was not taken into consideration. Consequently, an equal failure probability was considered for the evaluating nodes, although we are aware that pipelines may cross through a variety of soils, water corridors, and densely populated areas that define a space-dependent degradation process and failure probability. A sound extension of this work would incorporate the failure probability along the pipeline abscissa and the physical events they may produce once an LOC takes place.

In addition, the reader should note that even though pipeline operators follow the guidelines reported in standards like ASME B31.4 or CSA Z662, there is no uniform practice for the placing of these valves along the pipeline for Oil & Gas companies. Indeed, the location of pipelines depends on their being accessible for maintenance and reparation crews (Mohitpour et al., 2004) or when hydrostatic testing are facilitated (Menon, 2011). These additional valves can be incorporated into the model.

5. Conclusions and future perspectives

In this paper, an optimization model to solve the valve location problem for liquid hydrocarbon transportation is presented. The model seeks to minimize the expected economic losses and sectioning alternative costs while considering the restrictions of recognized current guidelines. The optimization-based model was tested on a real instance with a broad range in altimetry and a varied mountainous profile along the pipeline, and the results improve the current situation in terms of economic losses.

The model selects valve configuration according to potential spill volume calculations, cost estimations for LOC accidents, and cost estimation for the sectioning alternative. The model prioritizes the valve location to minimize the overall total cost throughout the pipeline by considering the type of commodity transported, pipeline configuration (i.e., underground), and high-consequence area classification. The sectioning alternatives suggested by the model are expected to obtain reductions on the order of 10%–18% in the total expected cost of economic losses of LOC accidents compared to the sectioning carried out under the guidelines reported in CSA Z662. Consequently, the model achieves an epistemic reduction of uncertainty by reducing the expected cost of economic losses.

The evaluation in a real instance showed that distances of 100 m and 200 m between nodes might be adequate for sectioning valves in the proposed approach, which represented a cost reduction of nearly 18% from the approach reported in CSA Z662. The results indicate that a bigger number of valves do not necessarily mean a more significant reduction in spilled volumes or expected costs of LOC accidents. Therefore, it is essential to identify critical points along the pipeline to make effective the valve configurations, thereby achieving a meaningful reduction with fewer valves.

Regarding the future perspectives, indexes of maintenance operations and accessibility could be incorporate to the model and a stochastic behavior of the degradation system can be implemented in a further space-dependent reliability analysis. Valve closure profiles and times can also be incorporated into the model, which might provide a suitable approximation for calculating the dynamic spill volume. Finally, additional multi-objective approaches for solving the optimization model could be evaluated.

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Nomenclature and abbreviations

β_k^l	k = 0,1 Linear regression coefficients for the l sub cost
$\dot{V}$	Dynamic volume spilled
$\mathscr{A}$	Set of possible arcs
$\mathscr{E}$	Set of sub costs
$\mathscr{G}(\cdot,\cdot)$	Graph with a set of nodes and arcs
$\mathscr{V}$	Set of nodes: Location of possible valves
$\tilde{V}$	Total volume spilled
C_T	Total cost
C_{Capex}	Cost of CAPEX
C_{ijl}	Economic proxy function
C_{Opex}	Cost of OPEX
C_{SA}	Cost of sectioning alternative
$f_l(V_{i,j}, x_{ij}, P_{ij})$	Expected cost for each sub cost
P_{ij}	Probability of failure of an arc
V	Static volume spilled
V_{ij}	Expected static volume for the arc (i, j)
x_{ij}	Node indicator function
CAPEX	Capital Expenditures
CFR	Code of Federal Regulation
CONCAWE	Conservation of Clean Air and Water in Europe
CSA	Canadian Standard Association
DOT	Department of Transportation
ILI	In-Line Inspection
LOC	Loss of Containment
OPEX	Operating Expenses
PHMSA	Pipeline and Hazardous Materials Safety Administration
TSB	Transportation Safety Board of Canada

Appendix A. Statistics for linear regression models

Conf.	VARIABLES/ SUBCOST	Public and non-Operator private property damage	Commodity lost	Operator's property damage & repairs	Operator's emergency response	Operator's environmental remediation	Other
CrOil Undgr HighPop	VOLUME (BBLS)	1553*** (125)	26.27*** (4.418)	524.7*** (79.1)	6815*** (1733)	3100*** (279.6)	1171*** (345.6)
	Observations	61	61	61	61	61	61
	R-squared	0.72	0.37	0.42	0.21	0.67	0.16
CrOil NonUndgr HighPop	VOLUME (BBLS)	237.6** (103.6)	309.8*** (83.77)		2814*** (585.8)	1561*** (495)	1780*** (492.8)
	Observations	90	90	90	90	90	90
	R-squared	0.06	0.13	0.025[na]	0.21	0.10	0.13
CrOil Undgr OtherPop	VOLUME (BBLS)	1294*** (49.49)	7.99*** (1.06)	182.3* (94.65)	8685*** (645.4)	29,439*** (1451)	249.1* (135.7)
	Constant		5571* (2879)	451,982* (255,916)			
	Observations	65	65	65	65	65	65
	R-squared	0.91	0.47	0.06	0.74	0.86	0.05
CrOil NonUndgr OtherPop	VOLUME (BBLS)		67.25*** (4.158)	897.4*** (156.9)	529.1*** (36.69)	550.8*** (24.16)	
	Observations	70	70	70	70	70	70
	R-squared	0.00[na]	0.79	0.32	0.75	0.88	0.00[na]
CrOil Undgr NonHCA	VOLUME (BBLS)	13.17** (5.29)	63.03*** (1.01)	30.74* (16.23)	255.0*** (37.11)	559.9*** (27.47)	
	Constant	13,226* (7299)			130,679** (51,222)	85,933** (37,923)	
	Observations	287	287	287	287	287	287
	R-squared	0.02	0.93	0.01	0.14	0.59	0.00[na]
CrOil NonUndgr NonHCA	VOLUME (BBLS)		34.52*** (1.40)	264.5*** (75.14)	22.91*** (5.77)	42.04*** (4.57)	
	Constant				16,136*** (4421)	16,826*** (3501)	
	Observations	504	504	504	504	504	504
	R-squared	0.00[na]	0.55	0.02	0.03	0.14	0.00[na]
Refn Undgr HighPop	VOLUME (BBLS)	394.4*** (77.32)	61.62*** (6.97)	1058** (460.8)	3449*** (527.5)	1935*** (223.7)	
	Observations	76	76	76	76	76	76
	R-squared	0.26	0.51	0.07	0.36	0.50	0.02 [na]
Refn NonUndgr HighPop	VOLUME (BBLS)		48.17*** (3.58)		119.7*** (18.11)	562.6*** (43.04)	
	Constant				13,620*** (2678)	14,720** (6366)	
	Observations	264	264	264	264	264	264
	R-squared	0.00[na]	0.41	0.00[na]	0.14	0.39	0.00[na]
Refn Undgr OtherPop	VOLUME (BBLS)		119.2*** (7.19)	1799*** (629.8)	953.4*** (278.1)		
	Observations	33	33	33	33	33	33
	R-squared	0.06[na]	0.89	0.20	0.27	0.08[na]	0.03[na]
Refn NonUndgr OtherPop	VOLUME (BBLS)		32.70*** (5.99)		103.7*** (29.67)	93.89*** (27.41)	12.72* (7.50)
	Observations	108	108	108	108	108	108
	R-squared	0.00[na]	0.22	0.00[na]	0.10	0.1	0.03
Refn Undgr NonHCA	VOLUME (BBLS)	16.08** (6.90)	61.18*** (2.66)	27.58** (11.99)	825.5*** (96.29)	1163*** (107.5)	
	Constant		6142* (3306)	57,557*** (14,890)			
	Observations	128	128	128	128	128	128
	R-squared	0.04	0.81	0.04	0.37	0.48	0.01[na]
Refn NonUndgr NonHCA	VOLUME (BBLS)	29.39** (13.95)	52.23*** (2.04)		375.2*** (90.39)	1446*** (443.4)	
	Constant		303.6* (179.5)		21,160*** (7936)		
	Observations	171	171	171	171	171	171
	R-squared	0.03	0.79	0.00[na]	0.09	0.06	0.00[na]

Standard errors in parentheses. *** $p - value < 0.01$, ** $p - value < 0.05$, * $p - value < 0.1$, [na] Not available model.

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