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Optimal Sectioning of Hydrocarbon Transport Pipeline by Volume Minimization, and Environmental and Social Vulnerability Assessment

John Fontecha*[a], A. Cano-Acosta[a], Nubia Velasco[b], F Muñoz-Giraldo[a]
[a]*Grupo de Diseño de Productos y Procesos (GDPP). Department of Chemical Engineering*
[b]*School of Management.*
Universidad de los Andes
Carrera 1 No. 18A-10, Bogotá, Colombia

* Presenter E-mail: je.fontecha10@uniandes.edu.co

Abstract

Sectioning is one of the key mitigation strategies in pipeline transport of liquid hydrocarbons. The valves located along pipelines reduce the maximum volume that may be spilled, decreasing economic, social and environmental losses. Defining the location and number of valves in a specific pipeline section is a challenge due to the countless combinations of these two design components (i.e., where and how many valves). In this work, we tackle the valve location problem (VLP) for sectioning. To solve the problem, we use an optimization approach which assesses the number and location of valves to minimize environmental and social consequences. This problem is modeled as a shortest path problem and it considers the maximum volume that could be spilled as well as environmental and social issues. To estimate and quantify the damages (environmental and social) a new framework is proposed. We present a case study for sectioning in a pipeline of Colombia; the problem is solved using a Bellman-Ford algorithm with CPU times up to 32 s. The results show reductions around 75% of the maximum possible spilled volume. The resulting valve configurations cover areas with high vulnerability, guarantying individual risks lower than the acceptable risk on all populated areas.

1. Introduction

The installation of flow cut devices (e.g. valves) to split pipeline in segments is known as sectioning. This mitigation strategy enables the isolation of a pipeline segment when a primary loss of containment (LOC) takes place. The primary objective of isolation is to straiten the amount of spilled volume [1]. Since the social and environmental risks associated with hydrocarbon transportation are directly related to the spilled volume, sectioning represents a tool for minimizing those risks. The challenge here is to define the location/number of valves more suitable to accomplish the primary objective.

Commonly, this challenge is faced with legislation, international standards and recommended practices (RP) such as US DOT CFR 195.260-195.179 [2, 3], ANSI/ASME B31.4 [4], CSA Z662 [5] and BS 1416 [1]. These are prescriptive approaches and assess sectioning based on general criteria (mostly related to the social characteristics of an area) and define a maximum distance between valves. Since this first approximation does not consider particularities of the system, environmental vulnerable areas and the operating conditions of each pipeline, new approaches are being developed. New approaches usually are based on the performance of the system, potential spill volume, risk calculations, and in some cases they are coupled with optimization models [6-11]. An example of these approaches is the Intelligent Valve Placement (IVP) approach, which considers risk reduction instead of commonly used rule-of-thumbs and regulatory requirements [9].

Weir [9] has developed the IVP approach in order to identify optimum valves locations on existing pipelines in the United States. The Weir approach [9] incorporates risk through reduction of consequence, reducing the potential spill volumes and impact to sensitive areas in an iterative manner. In recent years, he has worked to improve the IVP approach. For instance, Weir and Li [8] enhanced the IVP approach to optimize valve placement based on the effectiveness and potential volume out reduction of valves, the former being a measure that quantifies how effectively a valve reduces spill volume in pipe sections which possibly affect one or more identified sensitive areas. However, this measure does not work well with significant spill volume reduction potential with few or no sensitive areas associated, so the potential spill volume reduction related with a given valve must also be considered. Due to valve effectiveness limitations, recent incidents and higher public awareness about requirements to mitigate environmental impacts concerns in the case of pipeline rupture, Weir [10] reevaluated and refined the IVP approach. The enhancements include a) set valve spacing for high vapor pressure (HVP) pipelines, b) a new definition of major water crossing (was 100 feet wide or greater), c) tighter volume out thresholds, and d) application of a value assessment applied to the placement of valves for pipeline sections in areas that may or may not contain high consequence areas.

On the other hand, Rout [11] presents a solution to the challenge implicit in valve placement optimization, in both interconnected and isolated systems by iteratively generating valve placement scenarios and hydraulic modeling. They calibrated their results with real-world incidents.

Grigoriev [7] wanted to develop an algorithm to solve the following problem: given a pipeline structure and a number of shutoff valves to be placed, how would it be possible to find adequate valve locations in order to minimize the maximum environmental damage of an oil spill. They formulated the problem in terms of graph theory in which a pipeline is represented as a network. Let $G = (V, E)$ be an undirected graph representing a pipe network where V is the set of vertices and E is the set of edges, the latter being a representation of pipes. Vertices with $d(v) = 1$ are the source and destinations of the pipeline and vertices with $d(v) \geq 2$ represent connection points between the pipes, where $d(v)$ is the degree of the vertex $v \in V$ (i.e., how many edges are connected - odd or even - with $v \in V$). ω_e denotes the length of the pipe $e \in E$ and k the number of valves to be installed and can be located in any vertex $v \in V$ [12].

Furthermore, Grigoriev [7] presented the first complete decision framework for fast computing a solution for the presented problem. To achieve this, they calculated environmental damage using weights of ecological damage for each pipe, which are dependent on the landscape surrounding each pipe, and maximum volume of oil escape. Then, they started solving the simplest pipe network where the valves should be installed along a linear pipeline segment using two fast algorithms, a dynamic programming algorithm and a binary search "guessing" algorithm. Moreover, they used these results to design another dynamic programming algorithm to compute an optimal valves allocation along linear segments of a general and more realistic pipe network. Comparing their results with currently used valve location solutions, it was demonstrated that the solutions provided by the designed framework reduce ecologic damage up to 37%.

Similar to Grigoriev [6, 7], Medina [13] wanted to develop a methodology that takes into account optimization criteria and risk quantification consideration to solve the valve location problem (VLP). They proposed an optimization methodology in which an objective function that analyzes the variation in overall costs, including pipeline cost and the cost of accidents that may occur is used. The decision variable is the number of intermediate shutdown valves, which establish the amount of hazardous material spilled in the event of containment loss. The optimum design leads to the minimization of overall cost. On this approximation potential spill volume calculations are performed and its results introduced on a mathematical model to simulate the dispersion of the liquid hydrocarbon on soil and groundwater and determine volumes of contaminated material for both. Using the costs of treatments to remove the pollutants, the total cost of the consequences is estimated and put into an objective function with the cost of the equipment. It is assumed that the valves are equidistant. The optimization methodology was applied to the transportation of gasoline by a pipeline of 8" and 200 km length, where the minimum cost was found with 8 valves and an optimal distance of 22.2 km. It is important to outline that the optimum value will also be a function of soil properties.

It is important to highlight that the works studied here try to incorporate risk and consequence reduction as the same as optimization to find the optimal number and location of valves in order to minimize cost and risk, instead of using heuristic criteria. Based on the work of Grigorieva [6, 7] and Medina [13] this VLP can be seen as a shortest path problem by the quantification of the environmental vulnerability as index. On this work these indexes are put into a framework that depends on the severity of the spill given the specific ecological characteristics of the area, including not just soil and groundwater contamination but ecosystems and superficial water sources degradation. This is a part of the objective function related also with the potential spill volume calculated with a source model. This shortest path problem is solved with the Bellman-Ford algorithm. To tackle the social risk, the definition of tolerable individual risk is incorporated as a constraint to the model so the individual risks are calculated by the methodology on the entire pipeline and then evaluated to decide if a sectioning alternative is viable in social terms.

The rest of this paper is organized as follows: Section 2 formally defines the problem and notation. Section 3 provides the methodology proposed, which is divided in two stages. First a parameter calculation framework is presented. Then, an optimization approach is defined. Section 4 shows the application of the methodology to the case study. Section 5 concludes the work and outlines future research guidelines.

2. Problem statement

The VLP problem that hydrocarbon transport operators face looks for determining the minimal number of valves to install and their location in a long pipeline, minimizing the risks associated with the potential spill volume.

Consider a pipeline from a defined origin to a defined destination; to model the problem a direct graph $\mathcal{G}(\mathcal{V},\mathcal{A})$ is used. A discrete point $i \in \mathcal{V}$ exists if it is possible to place a valve over it. Nodes 0 and n are the beginning and the end of the pipeline, respectively. Each node is characterized by a geographical position and an altimetry (x, y coordinates) as shown in Figure 1. The set $\mathcal{A} = \{(i,j): i,j \in \mathcal{V}, i < j\}$ is the set of arcs representing all possible connections between a consecutive pair of valves, as shown in Figure 2. For every arc $(i,j) \in \mathcal{A}$ ∃ there are d_{ij}, V_{ij}, RI_{ij}, R_{ij} representing the distance, the potential spill volume, the individual risk and the total risk associated with the section between i and j, respectively. Additionally, the index a_i for each $i \in \mathcal{V} \backslash i = n$ is the environmental vulnerability index in the segment $(i, i+1)$. An arc (i,j) $\in \mathcal{A}$ exists, if and only if $d_{ij} \leq d_{max}, RI_{ij} < RI_{max}$, where d_{max} is the maximum recommended distance by CSAZ662 and RI_{max} is the tolerable individual risk.

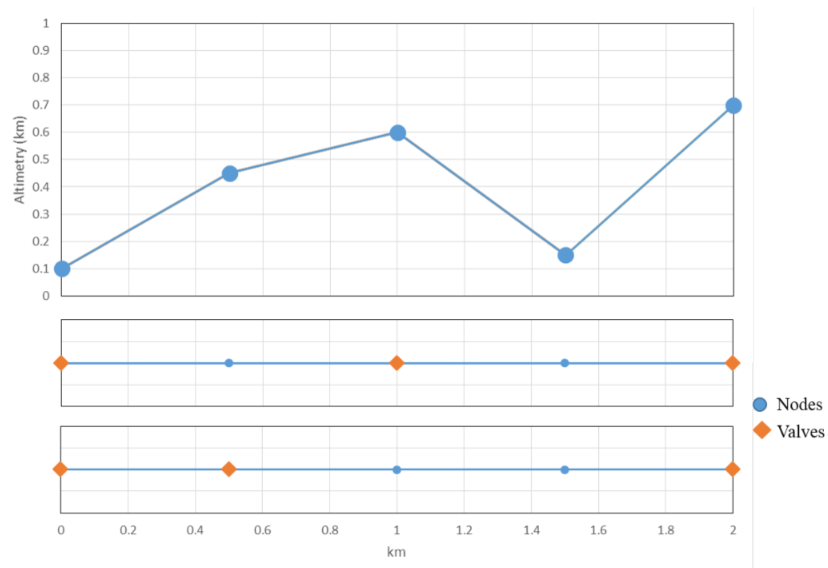

Figure 1. Illustration of a linear pipeline segment with connection points (nodes) each 500 m. Two different configurations of valve location are presented.

The goal is to find a route $r \in \mathcal{R}$ (where $\mathcal{R}$ is the set of all feasible routes, i.e., valve configurations) that minimizes the total risk. A route is a path that starts at node 0, flowing along of the network until it arrives to node n, each node on this route being a valve location point.

For example, on Figure 3 a feasible route is $\{(0,2),(2,4)\}$ with a total risk of 10, meaning that over this pipeline, locating valves on points {0,2,4} produces a risk (route cost) of 10. To illustrate all of this, two different configurations of valve location are represented on the graph $\mathcal{G}$ in Figure 3 from configurations presented in Figure 1.

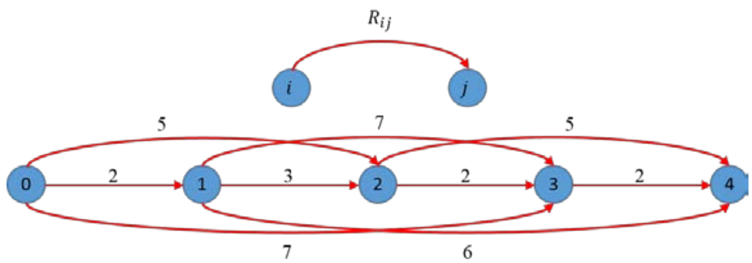

Figure 2. Graph $\mathcal{G}(\mathcal{V},\mathcal{A})$ representing the pipeline from Figure 1. In this example $d_{max} = 1.5$ km.

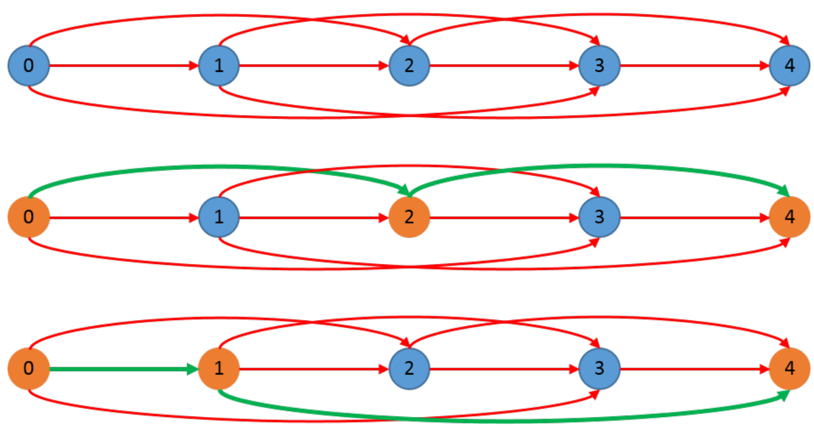

Figure 3. Two different configurations from Figure 1 are presented over graph $\mathcal{G}(\mathcal{V},\mathcal{A})$. a) locate valves on $\{0,2,4\}$ with a risk cost equal to 10, b) locate valves on $\{0,1,4\}$with a risk cost equal to 8.

3. Methodology

In this work, we follow a similar structure developed by Grigoriev and Grigorieva [6, 7] in order to attack the valve location problem (VLP). However, we use a directed graph to represent the VLP and we solve the problem using a specialized algorithm for the shortest path problem. To solve the model, we need parametric information about environmental and social risk. Then, we need to calculate the parametric values and after that, we can run the optimization model.

This section is organized as follows: first, we define the parameter calculation framework to evaluate different kinds of risks (i.e., social and environmental). Then, we present the optimization model and the respective solution strategy. Finally, we discuss four different approaches for the risk estimation.

3.1. Parameter calculation framework

To develop a sectioning alternative, the optimization around the stated problem is based on three criteria: 1) maximum spilled volume (when a failure occurs); 2) environmental vulnerability; and 3) social vulnerability. The environmental and social vulnerabilities are assessed by an index and individual risk calculations, respectively (Figure 4). Based on the general structure it is important to describe the way each criteria is assessed and quantified.

3.1.1. Potential spill volume calculation

The potential spill volume (V) can be divided on two main contributions: 1) dynamic volume and 2) static volume. The first one is related to the flow before valve closure and the second one is related to hydrostatic charges after valve closure as shown in Figure 5. The dynamic volume is assumed constant by the worst case scenario, calculated by the product between the maximum flow rate and the maximum closure time of valves. In order to decrease the calculus complexity, we use a non-rigorous source model to evaluate the static volume. This problem can be solved as a liquid spill on vertical tanks [14]. We evaluate the volume V_{ij} as presented in equation (1).

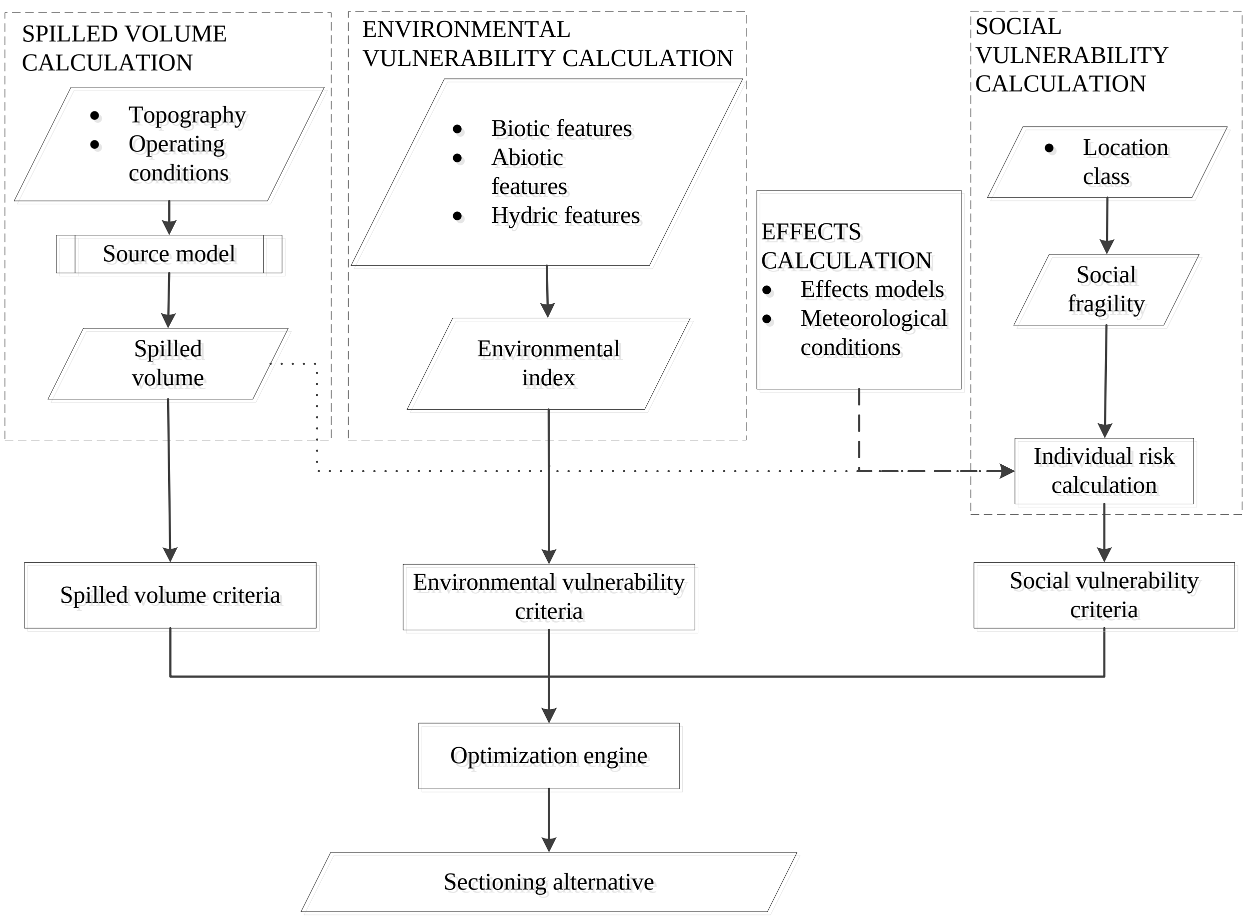

Figure 4. Parameter calculation framework and optimization.

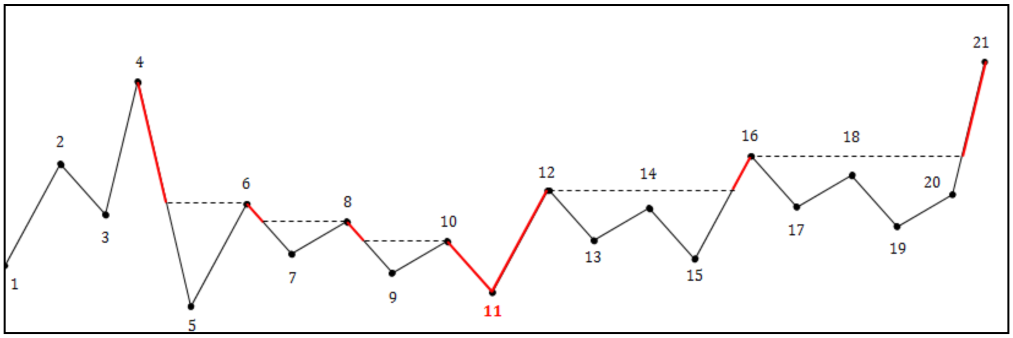

Figure 5. Illustration of hydrostatic charge.

$$V_{ij} = \max_{i \le k < j} V_k \quad \forall (i,j) \in \mathcal{A} \tag{1}$$

3.1.2. Environmental vulnerability calculation

The environmental vulnerability is quantified by an environmental vulnerability index (a). This one depends on the intrinsic characteristics of the area classified in three major groups: 1) abiotic factors; 2) biotic factors; and 3) hydric factors (Figure 6) [14-23].

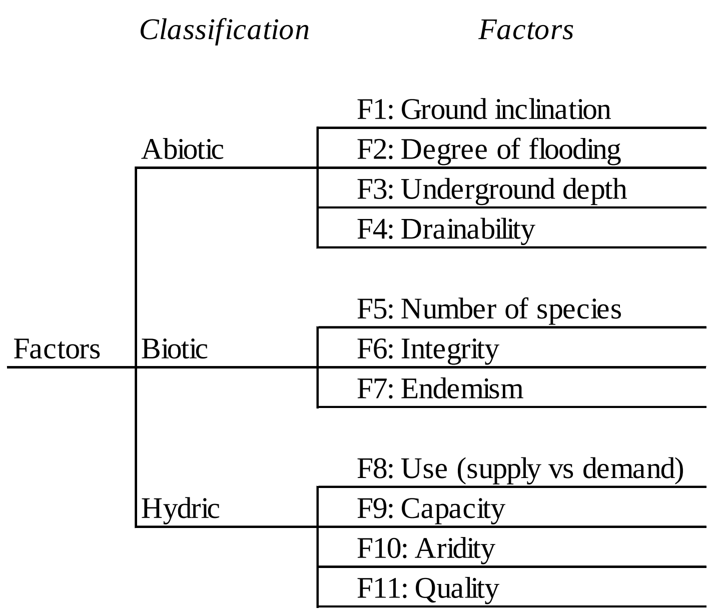

Figure 6. Environmental factors for vulnerability index calculations [14-23]

We propose dividing each factor on 5 levels with a weight between 0 and 1 depending on the severity of a spill based on given specific conditions. Then, in the proposal 0 is very low severity, 0.25 is low severity, 0.5 is medium severity, 0.75 is high severity and 1 is very high severity. Finally, the index a_i for each $i \in \mathcal{V}$ is calculated by the sum of the weights of all factors normalized by the highest potential spill volume over the lowest potential spill volume.

3.1.3. Social vulnerability calculation

The social vulnerability calculation is assessed by individual risk calculations. The events and their probabilities are assessed by the construction of a generic event tree (Figure 7), where the probability of immediate ignition (P_1 and $\overline{P_1}$) depends on the flammability of the substance, delayed ignition probability (P_2 and $\overline{P_2}$) depends on the population density and the front flame acceleration (P_3 and $\overline{P_3}$) depends on the confinement level [25, 26].

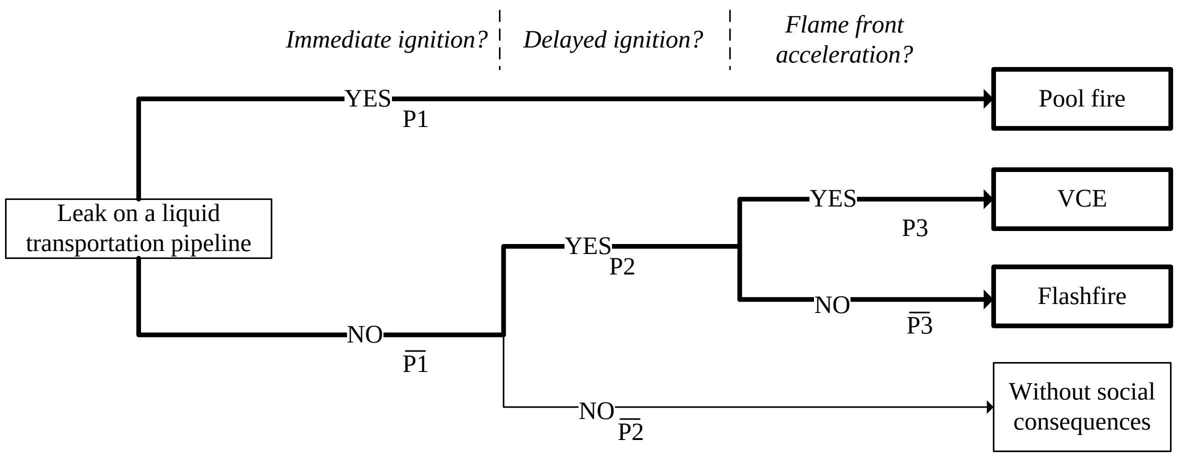

Figure 7. Generic event tree [25]

The consequences associated with a 100% probability of one fatality as a result of the event $e \in \mathcal{E}$ (PF_e), where $\mathcal{E}$ is the set of possible events, are calculated on the specialized software Effects, where relations between the amount of spilled volume and the lethal distance ($D(V)$) are constructed for different substances and incorporated into the methodology. As a last stage, the respective probabilities (P_e), consequences along with the failure frequency (f), and the length of interest (L) are used to calculate the individual risk with equation (2), while L is calculated with equation (3). Note in equation (3) that L depends on $D(V)$, and $D(V)$ depends on amount of spilled volume. If we know the potential spill volume given a possible location of valves in (i, j), then, we can calculate a RI_{ij} for each $(i, j) \in \mathcal{A}$ from equations (2) and (3).

$$RI = fL \sum_{e \in \mathcal{E}} P_e * PF_e \quad (2)$$

$$L = 2 * \sqrt{D(V)^2 - d^2} + l \quad (3)$$

Where d and l are the distance between the pipeline and the population and the size of the last one respectively. The value of the individual risk is then compared with the tolerable value and incorporated into the model as shown on the Problem Statement section.

3.2. Optimization model and Bellman–Ford algorithm

Let R be a risk function composed by the product between potential spill volume V and the environmental vulnerability index a. We can define R_{ij} as presented in equation (4). With this we can define the optimization model.

$$R_{ij} = \max_{i \le k < j} a_k V_k \quad \forall (i,j) \in \mathcal{A} \tag{4}$$

If we define x_{ij} as a binary variable that takes 1 if valves are located in $i \in \mathcal{V}$ and $j \in \mathcal{V}$, 0 otherwise, then, we can write the optimization model as follows:

$$\min \sum_{(i,j) \in \mathcal{A}} R_{ij} x_{ij} \tag{5}$$

s.t

$$\sum_{(ij) \in \mathcal{A}} x_{ij} - \sum_{(ji) \in \mathcal{A}} x_{ji} = \begin{cases} 1 & i = 0 \\ 0 & \forall i \in \mathcal{V} \backslash i \in \{0, n\} \\ -1 & i = n \end{cases} \tag{6}$$

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

Equation (5) minimizes the risk according to the valve configuration. The set of constraints (6) models the balance in each node in order to ensure that path flows in the network from 0 until it arrives to n; the set of constraints (7) describes the nature of the decision variables. Observe that integrality of the variables is relaxed in the set of equation (7), in order to reduce the complexity of the optimization. Modeling the problem in a network permits this relaxation assuring that the solution of variables is integer (binary) [27].

This problem can be solved as a linear problem with simplex algorithm and using some optimizer as Gurobi, but in this case, we can use a specialized in shortest path algorithm. The algorithm implemented to solve this model is the Bellman-Ford algorithm [28].

Algorithm 1: Bellman-Ford Algorithm [28]

$\boldsymbol{v_0 := 0}$
for $i \in \mathcal{V} | i \neq 0$
    $v_i := \infty$
end for
for $i \in \boldsymbol{\mathcal{V}} | i \neq \{0, n\}$
    for $j \in \mathcal{V} | (i,j) \in \mathcal{A}$
        if $v_i + R_{ij} < v_j$ **then**
            $v_j = v_i + R_{ij}$
            $P_j = i$
        end if
    end for
end for

To assess the effect of the minimum distance between consecutive pairs of connection points (nodes), four distances between nodes are evaluated: 100 m, 200 m, 300 m and 500 m. To illustrate this, Figure 1 shows a minimum distance between two nodes of 500 m.

3.3. Four different approaches for the risk estimation

The volume considered on the arcs was evaluated in four different ways: 1) considering maximum potential static spilled volume as a shown in equation (4), 2) considering maximum potential static spilled volume plus the dynamic spilled volume as shown in equation (8), 3) considering average potential static spilled volume as shown in equation (9), and 4) considering the difference between a calculation basis (BigM) and the third approximation as shown in equation (10).

$$R_{ij} = \max_{i \le k < j} a_k (V_k + \dot{V}) \qquad \forall (i,j) \in \mathcal{A} \tag{8}$$

$$R_{ij} = \frac{1}{j-i} \sum_{i \le k < j} a_k V_k \qquad \forall (i,j) \in \mathcal{A} \tag{9}$$

$$R_{ij} = BigM - \left(\frac{1}{j-i} \sum_{i \le k < j} a_k V_k \right) \qquad \forall (i,j) \in \mathcal{A} \tag{10}$$

4. Case study

The methodology was implemented on an existing jet fuel transport pipeline in Latin America on a highlands area characterized by the variety of ecosystems and the presence of urban and suburban populations on some segments of the pipeline. The altimetry profile is shown on Figure 8. It can be observed that the highest changes on the slope are between the 70 km and the 100 km of the abscissa, where the highest spilled volumes are expected. Results presented considering spilled volumes without valves, environmental vulnerability indexes, valve locations and related spilled volumes for each minimum distance (between consecutive nodes - described before) and for each spilled volume approximation. Finally, individual risk calculations and validation are shown.

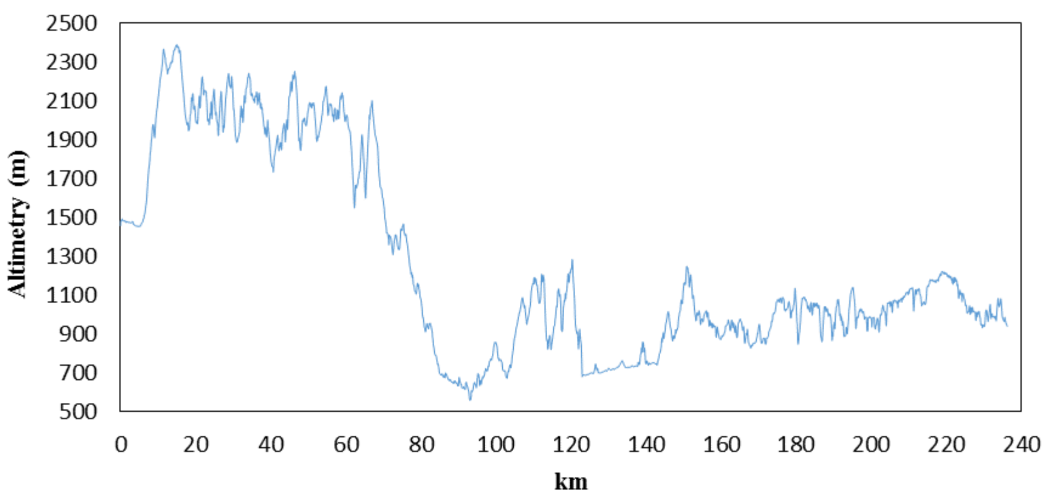

Figure 8. Altimetry profile of the pipeline

For the decision making process the potential spill volume and environmental indexes must be calculated along with the identification of the populated areas and their categorization on class locations (implementing the definitions stated by the CSA Z662). The maximum potential spill volumes on the pipeline correspond to the biggest slope as expected (between 80 km and 100 km) with 6000 bbl of spilled volume expected. The maximum vulnerability indexes are between the 60 km and 100 km and between 140 km and 210 km coinciding with the higher potential spill volumes in the first case. The index takes values between 4 and 4.5 due to the presence of forests and moors and when peaks can be observed (163 km and 180 km) there is also presence of hydric sources. Finally, suburban populations are present on the first kilometers of the pipeline and on kilometer 170, while an urban population is located in the last kilometers (see Figure 9).

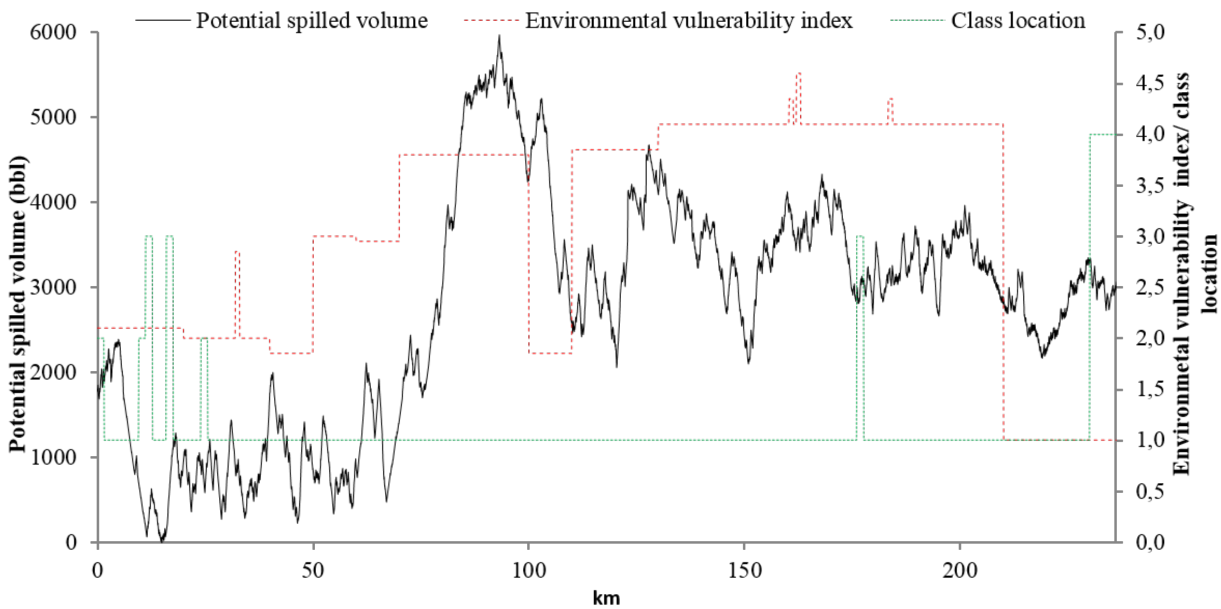

Figure 9. Potential Spill volume, environmental vulnerability indexes and class locations for the pipeline

Having assessed the three components of the optimization for the entire pipeline, it is possible to run the optimization model. The results for the minimum distances of 100 m, 200 m, 300 m and 500 m are shown from Figure 10 to Figure 13 respectively; each one includes the results for the four spilled volume approximations and present the potential spill volume (colored bar) for the respective valve configuration, the valve location (geometrical figure), the number of valves and the maximum, minimum and average distance between valves.

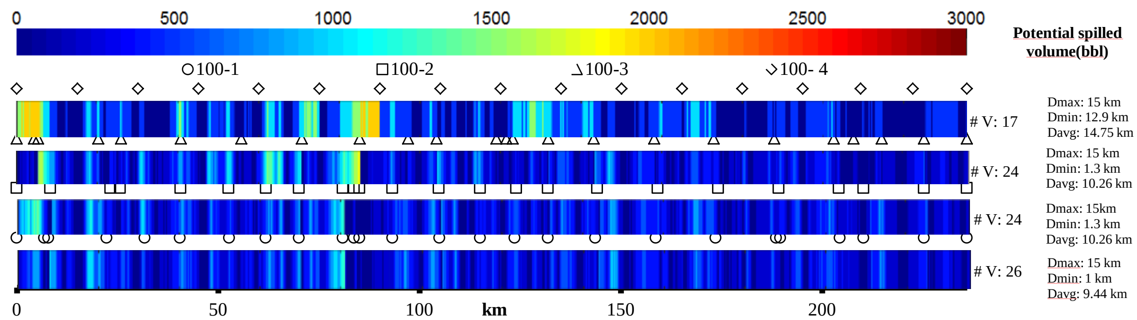

Figure 10. Potential spill volume, valve location, maximum distance between valves (Dmax), minimum distance between valves (Dmin), average distance between valves (Davg) and number of valves (# V) for a minimum distance of 100 m and the four volume approximations.

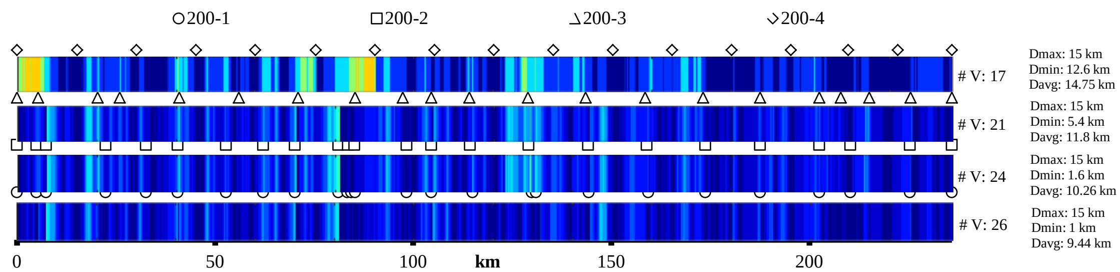

Figure 11. Potential spill volume, valve location, maximum distance between valves (Dmax), minimum distance between valves (Dmin) , average distance between valves (Davg) and number of valves (# V) for a minimum distance of 200 m and the four volume approximations.

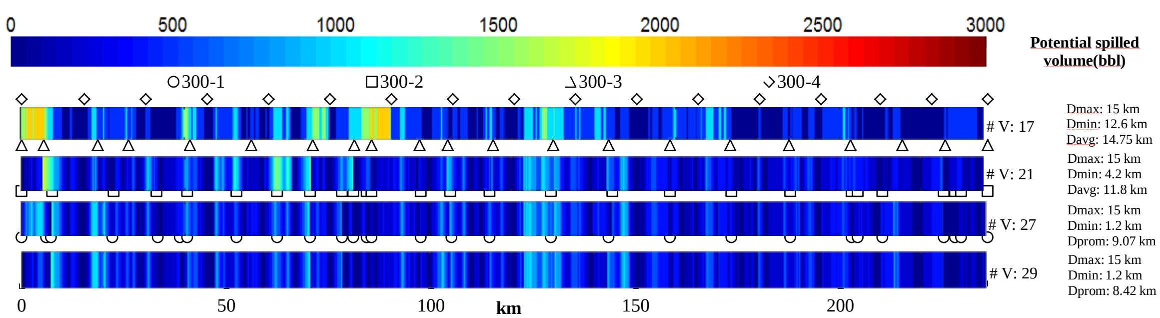

Figure 12. Potential spill volume, valve location, maximum distance between valves (Dmax), minimum distance between valves (Dmin), average distance between valves (Davg) and number of valves (# V) for a minimum distance of 300 m and the four volume approximations.

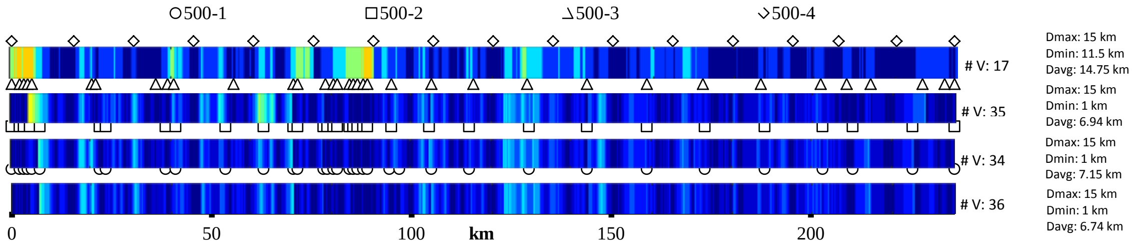

Figure 13. Potential spill volume, valve location, maximum distance between valves (Dmax), minimum distance between valves (Dmin), average distance between valves (Davg) and number of valves (# V) for a minimum distance of 500 m and the four volume approximations.

All the approximations for the risk estimation put a higher number of valves between 70 km and the 100 km due to the large amounts of potential spill volume and the high vulnerability indexes in the area. It also locates valves on strategic nodes like the nodes related to the presence of hydric sources like kilometer 163. In terms of spilled volume, the bigger reductions are achieved in the sensitive zones described above.

Comparing minimum distances between nodes, it can be observed that the larger distance presents higher number of valves, although it does not represent the higher reductions on potential spill volume. This tendency can be observed on the distances of 300 m 200 m and 100 m, achieving better potential spill volume reductions with less valves. This means that the location of the valves is indeed an important variable for sectioning, since better results can be achieved with fewer valves if they are positioned on strategic points of the pipeline.

Comparing volume approximations, it can be observed that the model loses sensibility with the fourth approximation since neither the number, nor the locations of the valves change. As expected, the locations of the valves between approximations one and two does not change since the only difference between them is the addition of the dynamic spilled volume modeled as a constant on the present work. Between using the maximum or the average spilled volume, it can be observed that in general, although they have a similar number of valves, average volumes represent configurations with higher potential spill volumes than the maximum spilled volume approximation.

The sectioning process for this specific case did not consider the populations surrounding the line because the individual risks calculated by the program are lower than the tolerable individual risk (10^{-4} fatalities/year) as shown in Figure 14, where the bigger populations located between 150 km and the end of the pipeline are displayed and have maximum individual risk values of $2*10^{-6}$.

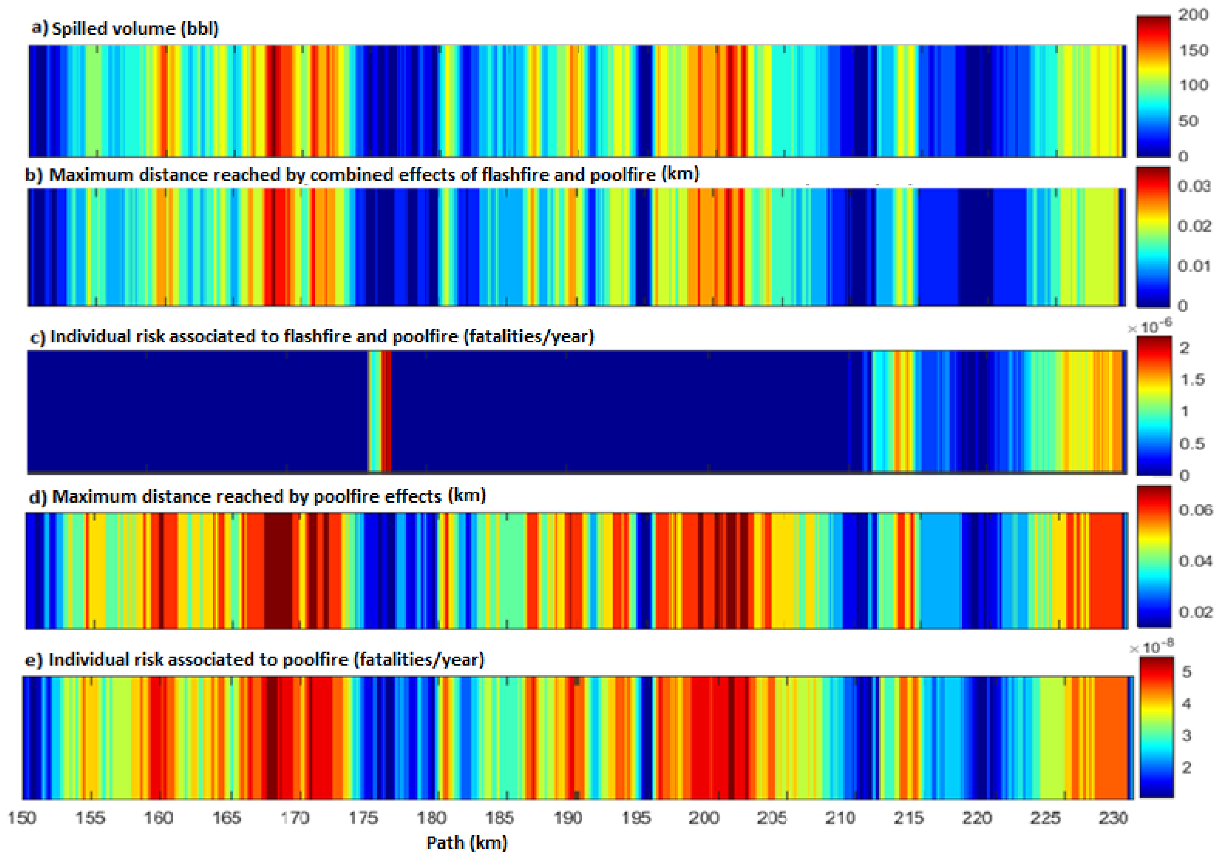

Figure 14. Individual risk calculations

To validate these values, two different points on the pipeline, one with flashfire and poolfire (210 km) and another with just poolfire (150 km) are evaluated on Risk Curves. As shown in Table 1, there is no difference between the values assessed by the present model and the ones obtained by Risk Curves.

Table 1. Individual risk validation with Risk Curves. a) Poolfire, b) Poolfire + flashfire

a)

Place (km)	Model		Risk Curves	
	Individual risk (fatalities/year)	Distance (m)	Individual risk (fatalities/year)	Distance (m)
150	2,08E-08	26	2,08E-08	26
210	2,18E-08	29	2,18E-08	29

b)

Place (km)	Model		Risk Curves	
	Individual risk (fatalities/year)	Distance (m)	Individual risk (fatalities/year)	Distance (m)
150	-	-	-	-
210	6,97E-07	5	6,97E-07	5

To evaluate the performance of the model, if unacceptable individual risks are present on the pipeline, values over 10^{-4} fatalities/year were randomly induced, and in all the cases an increase in the number of the valves was obtained. Thus, the model does take into account the maximum individual risk restriction.

Finally, the optimization cpu time is between 1 second and 32 seconds. The lowest optimization cpu times are related to the minimum distance of 500 m and goes in descending order, the higher times being the ones of 100 m.

5. Conclusions and future research guidelines

The developed model selected valve locations in function of potential spill volume amount, areas with high environmental vulnerabilities, assuring individual risks lower than the acceptable value on the populated areas. The individual risk calculations were validated by Risk Curves where no differences were found.

A larger number of valves does not necessarily imply a better spilled volume reduction, It is important to identify key points on the pipeline to achieve great reductions with fewer valves. The model is also flexible in terms of the known variables and information available about the surrounding areas.

When it comes to future perspective, it is important to incorporate indexes associated with accessibility for maintenance operations and production losses associated with agriculture. Valve closure profiles and times can also be incorporated to the model changing the way dynamic spilled volume is calculated.

Acknowledgements

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