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IFAC-PapersOnLine 49-12 (2016) 532–537

Shortest path algorithm for optimal sectioning of hydrocarbon transport pipeline

A. Cano-Acosta * John Fontecha *
Nubia Velasco**Felipe Muñoz-Giraldo*

* *Grupo de Diseño de Productos y Procesos (GDPP), Departament of Chemical Engineering, Universidad de los Andes, Bogotá-Colombia*
e-mail: {na.cano744, je.fontecha10, fmunoz} @ uniandes.edu.co).)
*** School of Management, Universidad de los Andes, Bogotá-Colombia*
(e-mail: nvelasco@uniandes.edu.co)

Abstract: Pipeline transportation mode is one of most used modes in oil industries. Transportation of hazardous substances by pipelines involves environmental, social and economic risks since a failure on a pipeline generates a subsequent release of a possible hazardous material. Limiting the amount of the spill volume reduces de losses and in consequence the associated risks; this mitigation is usually achieved by the installation of sectioning valves located along the pipeline. On practice a challenging problem is how much valves and where to locate them in function of the risks presented on each section. In this work, we tackle the valve location problem (VLP) for sectioning. This problem is modeled as a shortest path problem minimizing the maximum volume that could be spilled as well as environmental and social risks. To solve the problem we use the Bellman-Ford's algorithm, assessing the number and location of valves to minimize environmental and social consequences. The approach was tested on a case study for sectioning a pipeline in Colombia. The results show reductions around 75% of the maximum possible spilled volume and the resulting valve configurations effectively cover areas with high vulnerability, guarantying individual risks lower than the acceptable risk on all populated areas and protecting areas of environmental interest.

Keywords: Transportation, pipelines, shortest path problem, Bellman-Ford, risk

1. INTRODUCTION

When it comes the most popular mode to transport hazardous materials, specially hydrocarbons, the pipeline is the answer, especially because it is consider one of the safest and effective ways to cover long distances (Citro & Gagliardi, 2012). Although that does not mean accidents will not take place, it can be said that on a proper environment probabilities of a loss of containment (LOC) of a transported material by pipelines is low, but when an accident takes place the consequences can be catastrophic due to the difficulties to control the release high volumes can be spilled and an as consequence, the associated risks could be elevated. Those risks could generate environmental degradation and contamination, infrastructure and economical losses and in some cases health problems, injuries and fatalities for members of the populations involved (Citro & Gagliardi, 2012). A good example was the rupture of a pipeline in Michigan on 2010, where crude was released on the Kalamazoo River causing contamination of the river and near soil and forcing 60 families to evacuate, whom lately reported health problems associated mostly to the spill ("Investigating Environmental Impacts of the Kalamazoo River Oil Spill," 2012).

To mitigate these consequences multiple strategies have been proposed, mainly based on route selection and emergency shutdown systems implementation. The last ones are composed by pressure and flow sensors and sectioning valves.

The sectioning valves function limits the spilled volumes closing a set of valves once a LOC is detected reducing risks (Goodland, 2005). The valve location problem (VLP) looks for determining the minimal number of valves to install and their optimal location on transport pipelines to minimize potential spill volumes, environmental and social risks. It was initially assessed by governmental and industrial authorities such ASME (The American Society of Mechanical Engineers) (ASME, 2004; ASME/ANSI, 2012), BS (British Standards) (British Standard, 2003) and CSA (Canadian Standards Association) (Canadian Standards Association, 2011) providing a general maximum distances between valves. On the last years some authors have proposed new methodologies based on optimization strategies, most of them based on volume minimization or maximization of the effectiveness of valves. Among them Li and Weir (2012), Weir et al. (2006), and Weir and Li (2008) (Li & Weir, 2012; David A Weir, Kwan, & Power, 2006; David A. Weir & Li, 2008) incorporates risk through reduction of consequence, reducing the potential spill volumes and impact to sensitive areas in an iterative way including: a) set valve spacing for high vapour 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 (Rout, 2012) presents a solution to the challenge implicit in valve placement optimization, in

10.1016/j.ifacol.2016.07.686

both interconnected and isolated systems by iteratively generating valve placement scenarios and hydraulic modelling. The results were calibrated with real-world incidents.

Medina et al. (2012) (Medina, Arnaldos, Casal, Bonvicini, & Cozzani, 2012), a proposed an optimization methodology where the objective function includes pipeline cost and the potential accident costs.

Grigoriev and Grigorieva (2009) and Grigorieva and Grigoriev (2007) (Grigoriev & Grigorieva, 2009; Grigorieva & Grigoriev, 2007) developed an algorithm to minimize the maximum environmental damage produced by an oil spill given a pipeline structure and a number of shutoff valves to be placed. The author represents a pipeline as a network with the line discretized by nodes every 500 m and arcs defined by to possible valve locations evaluated thought the definition of environmental risks and spilled volumes, the problem is solved via two algorithms: a dynamic programming algorithm and a binary search "guessing" algorithm. The results served as input to another dynamic programming algorithm that computes an optimal valves allocation along linear segments of a general and more realistic pipeline network. The principal limitation of the model is that the number of valves is an input of the model that is not necessarily the optimal number of valves, the purpose of the model presented here is to find both, the optimal number of valves and their location, including social risk as optimization criteria on the model.

This paper is organized as follow. Section 2 states the problem; methodology and solution approach is presented on section 3. A case study is analysed on section 4. Finally, section 5 concludes the research.

2. PROBLEM STATEMENT

The VLP could be defined over a direct acyclic graph $\mathcal{G}(\mathcal{V},\mathcal{A})$ that represents a pipeline from an origin 0 to a destination n. $\mathcal{V}$ is the set of nodes composed of all points where is possible to locate a valve. Nodes 0 and n are the beginning and the end of the pipeline, respectively. Each node i is characterized by a geographical position (*x,y* coordinates) and an altimetry as shown in Figure 1 where the point i has coordinates x= distance to de source point and y= altitude, characterizing the hydrostatic charges, the set of arcs $\mathcal{A}=\{(i,j): i,j \in \mathcal{V}, i<j\}$ represents all possible connections between a consecutive pair of valves, as shown in Figure 2. A pair of examples of the possible configurations over Figure 2 are displayed in Figure 3 were the general risk for every arc (i,j) is described by: the distance (d_{ij}), the potential spill volume (V_{ij}), the individual risk (RI_{ij}) and the total risk R_{ij} 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)*. Finally 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 the standard CSAZ662 (Canadian Standards Association, 2011) and RI_{max} is the tolerable individual risk.

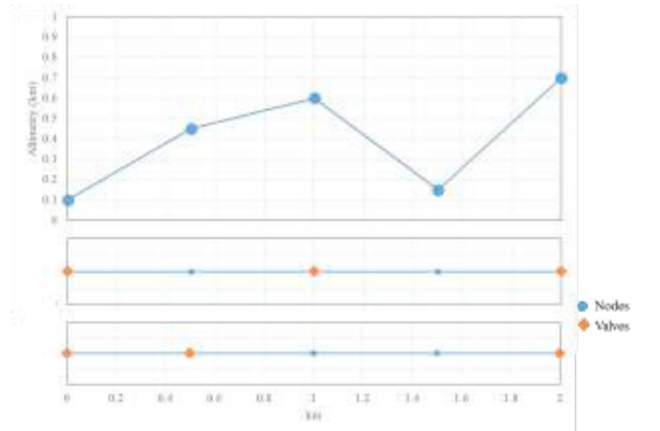

Figure 1. Illustration of a linear pipeline segment with connection points (nodes) each 500 m. Two different configurations of valve location are presented.

The purpose is to find a route $r \in \mathcal{R}$ (where $\mathcal{R}$ is the set of all feasible routes, i.e., valve configurations) from 0 to n made by an ordered sequence of arcs, that minimizes the total risk. 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. As an example two different configurations of valve location (routes) are represented on the graph $\mathcal{G}$ in Figure 3 from configurations presented in Figure 1.

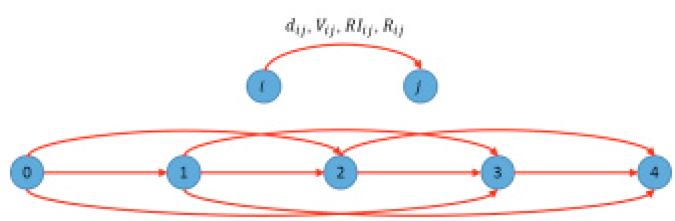

Figure 2. Graph $\mathcal{G}(\mathcal{V},\mathcal{A})$ representing the pipeline from Figure 1.

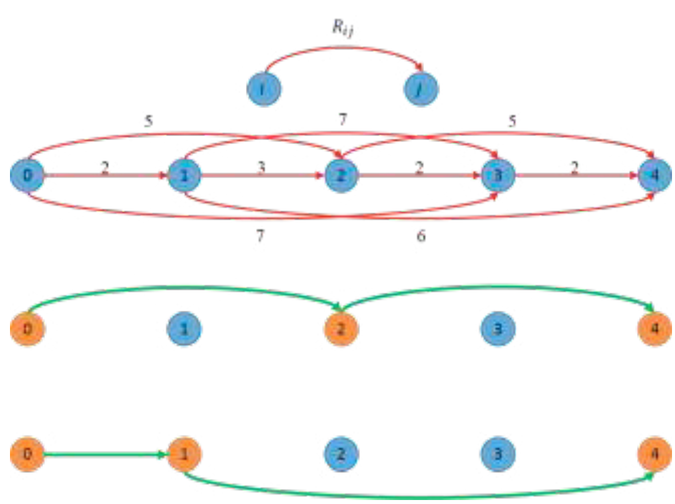

Figure 3. Two different configurations (routes) from Figure 1 are presented over graph $\mathcal{G}(\mathcal{V},\mathcal{A})$. a) locate valves on $\{0,2,4\}$ with a risk cost equal to 10, b) locate valves on $\{0,1,4\}$with a risk cost equal to 8.

3. METHODOLOGY

To solve the VLP first of all is necessary to estimate all problem parameters; which must obey to the description of social and environmental risks. The parameters are: the spilled volume, the environmental vulnerabilities and the social vulnerabilities (Figure 4).