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Multi-objective design optimization of natural gas transmission networks

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ABSTRACT

This paper proposes the multi-objective optimization of the design of natural gas transmission networks to support the decision of regulatory authorities. The problem formulation involves two objective functions: the minimization of the transportation fare and the maximization of the transported gas volume. These design parameters of the pipeline project must be previously established by the regulatory agency, considering an attractive return on the investment for the entrepreneurs and the demands of current and future consumers. The solution of this problem without an optimization tool may imply in unfair gas prices or the lack of investors interest. The proposed analysis is focused on growing markets, associated to a continuous increase of the natural gas consumption. Constraints associated to gas flow and compressor stations guarantee the feasibility of the set of design options found. Aiming to illustrate the performance of the proposed approach, the tool was applied to a typical trunkline example.

1. Introduction

Over the last 20 years, the global primary energy consumption has increased about 50 percent (OECD, 2013). This demand growth determines considerable technology and economic challenges to supply energy markets. This problem becomes even more complex when considering the environmental issues related to the greenhouse effect.

In this scenario, natural gas has become an important alternative of energy supply in the world energy matrix, e.g., natural gas consumption has been increasing more rapidly than any other fossil fuel (Economides and Wood, 2009). This crescent demand was particularly pronounced in some developing countries. For example, in the same 20 years span mentioned above, the natural gas consumption has increased eightfold in Brazil, ninefold in China and higher than threefold in India (BP, 2013).

The increase of the utilization of natural gas demands the planning, design and construction of an entire infrastructure for transporting the gas from the production fields to the consumers. A key component of this transportation system is composed of long transmission pipelines.

Because of its feature of natural monopoly (Braeutigam, 1989), the natural gas transportation sector is usually regulated by governmental agencies that establish general directives for new projects. In the USA, an interstate pipeline can be constructed only if it receives a Certificate of Public Convenience and Necessity from the Federal Energy Regulatory Commission (FERC). This commission authorizes the construction of a new pipeline after reviewing the project to determine its public interest (INGAA, 2009). In Brazil, the Brazilian National Agency of Petroleum, Natural Gas and Biofuels (ANP) is responsible by the regulation of the natural gas sector. New transmission pipelines are constructed according to a concession regime, where ANP establishes a public bid, identifying the gas pipeline route and the maximum fare for the gas transportation associated to a given internal rate of return.

The importance of gas transmission pipelines has attracted several investigations seeking to apply optimization techniques to support the design of gas transportation networks. The typical formulation of the design optimization problem consists in the dimensioning of the network main components in order to minimize the investment and operating costs. The investment encompasses the acquisition and construction of pipelines and compressor stations, and the operating costs involve the fuel costs to transport the gas along the pipelines. This problem can be addressed considering a given fixed set of supply and demand flow rates (Ruan et al., 2009; Tabkhi et al., 2009; Andre et al., 2009) or can be formulated considering the planning of the installation of

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the gas network according to a time horizon in the future (Kabirian and Hemmati, 2007).

A careful analysis of the literature indicates that the gas pipeline optimization problems previously investigated were focused on the maximization of the profit or the minimization of the costs. These approaches were formulated according to the point of view of the company that is responsible to design and/or operate the gas transportation network.

However, according to our knowledge, the analysis of the optimization problem considering the role of the regulatory agency to represent the public interest was not explored yet. In this context, the main novelty of our paper is the formulation of the optimization problem to guarantee that the project will be established harmonizing different aspects of the public interest by the regulation authority.

Because of multiple social pressures, the regulator must consider different impacts of a gas pipeline project simultaneously. Additionally, the project must be economically attractive to guarantee the necessary investments. This feature of the role of the regulator actor suggests the utilization of a multi-objective optimization tool for the determination of the specifications of a new project. Therefore, this paper is focused on the optimal determination of two key issues of a new project: the transport fare and the pipeline capacity.

The proposed analysis is based on growing markets, where, despite eventual economic fluctuations, it is expected a continuous increase in the natural gas demand. The need to supply a growing market presents an antagonistic pattern between the transport fare and the pipeline capacity. The increase of the amount of delivered gas during the time horizon imposes the construction of a larger pipeline, which penalizes the transportation fare. This trend occurs because the need to build a larger pipeline is associated to a higher idle capacity at the initial pipeline operation. This initial overcapacity will only be employed in the future, thus imposing a higher transportation fare to compensate the larger capital costs. Due to the existence of this trade-off, the proposal of the current paper is to handle this problem through the analysis of the optimal Pareto set obtained through the solution of a multi-objective optimization.

The resultant mathematical problem is a nonlinear programming (NLP) problem, where the identification of the Pareto set is conducted through the ϵ-constraint method. Aiming to guarantee the technical feasibility of the solutions found, the problem constraints include pipeline flow and gas compression equations. The resultant problem consists in a nonlinear programming (NLP) problem. The identification of the Pareto set is conducted through the ϵ-constraint method. Despite the higher complexity of multi-objective optimization, the need to consider multiple objective functions is a central aspect of the investigated problem. Multi-objective optimization techniques have been applied to several different problems in the chemical engineering field, such as, district heating design (Fazlollahi et al., 2014), design of supply chains for hydrogen production (Copado-Méndez et al., 2014), waste management (Capón-García et al., 2014), or natural gas network control (Zavala, 2014).

The rest of this paper is organized as follows: Section 2 describes the system investigated, Section 3 presents the formulation of the optimization problem, Section 4 presents the solution technique employed, Section 5 illustrates the utilization of the optimization scheme through its application to the design of a gas pipeline, and Section 6 discusses the final conclusions.

2. System investigated

The problem corresponds to the optimization of the design of a gas transmission network composed of one gas inlet point that is connected to one or more delivery points. The gas demand at the delivery points increases with time, representing the future behavior of the market during the horizon time of the project. Along the gas pipeline, there are compressor stations, which are responsible by the gas flow. The energy consumed by these compressor stations is supplied by a relatively small flow rate that is deviated from the main gas transportation flow. The route of the gas pipeline was already established, but the position of each compression station will be defined during the optimization. The set of design variables also contains the diameter and thickness of each pipe section and the power of the compression stations. Because of the crescent gas demand, the operational variables to be optimized (flow rates, pressures and compressor consumption powers) are organized in a multi-period framework.

In the investigated problem, the regulation process establishes that the project will be associated to a given fair internal return rate, coherent with the risks associated to this economic activity. The economic analysis of the project includes the investment in the pipeline sections and compressor stations and the operational costs associated to the fuel consumption to promote the gas flow. The corresponding revenue will be originated from the gas transportation fare.

According to this scenario, the regulator must define the scope of the project in terms of the transportation fare and the amount of gas that will be transported during the time horizon. The definition of the optimal set of these key values are the main goal of the decision process, considering that the public interest will ideally direct the answer to lower fares and larger amounts of gas transported.

However, an important aspect of the problem is that the delivery points represent growing markets, which are associated to a crescent demand curve. Therefore, the increase of the amount of delivered gas during the time horizon imposes the construction of a larger pipeline, which penalizes the transportation fare, i.e., these objectives may be in opposition to each other. Because of the existence of this trade-off, the proposal of the current paper is to handle this problem through the optimal Pareto set obtained through the solution of a multi-objective optimization. Therefore, the regulator actor will have an important auxiliary tool to judge the more adequate balance between these objectives.

3. Mathematical formulation

3.1. Network description

The gas transportation network is mathematically represented by a oriented graph G (Mah, 1990) where the nodes are identified by an index $n \in N$ and the edges are identified by an index $k \in K$. The set of edges represents the network elements, composed of two subsets: PI for pipe sections and CO for compression stations ($K = PI \cup CO$). The connection among the network elements is represented by the graph nodes. The set of nodes N is partitioned into the following subsets: PS for the network inlet node, PD for the delivery nodes, INT for the interconnection nodes, and SUC and $DISC$ for the suction and discharge nodes of the compression stations, respectively. According to the transported gas flow rate, the network digraph G is partitioned into branches G_j, such that, each branch is composed of pipe sections with same diameter.

3.2. Objective functions

The multi-objective optimization problem for the design of a natural gas transportation network is organized according to Eq. (1) where $\mathbf{x} \in \mathbb{R}^n$ is the vector of optimization variables, the first objective function $\Lambda(\mathbf{x}) : \mathbb{R}^n \to \mathbb{R}$ is the transportation fare in USD/MM BTU, the second objective function $V(\mathbf{x}) : \mathbb{R}^n \to \mathbb{R}$ is the total gas