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Optimization for design and operation of natural gas transmission networks

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HIGHLIGHTS

- Optimization for design or expansion of natural gas transmission networks.
- Integrated large-scale mixed-integer nonlinear optimization model to minimize investment and operating costs.
- Multi-period planning horizon.
- Pipeline and compressor station location and capacity selections.
- Extensive analysis on the design parameters to study trade-offs to support a sound and well-founded decision making process.

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ABSTRACT

We consider the problem of designing a new natural gas transmission network or expanding an existing network while minimizing the total investment and operating costs. We develop an integrated large-scale mixed-integer nonlinear optimization model to determine pipelines in the network, compressor stations and their capacities, timings of these installations in a multi-period planning horizon, and natural gas purchase and steady-state flow decisions for each period in the network. The model is solvable using state-of-the-art solution methodologies available online.

Employing our modeling and the solution methodology for its solution, we conduct computational studies on various test instances generated using realistic network structure and data based on the natural gas network in Turkey as well as data from literature. Our analysis provides insights into sensitivity of network configuration and operations to the number of periods within the planning horizon and cost parameters as well as into strategic decision making for design and expansion of natural gas networks.

1. Introduction

The continual increase in oil prices and environmental concerns have led natural gas (NG) to become one of the important energy sources in the world. With a growing population and economy, demand for NG has increased because of expanding industrial and commercial sectors, and growing income in the households. Today, natural gas accounts for 25% of the world's primary energy production. Globally, demand for natural gas is expected to grow at a rate of 2.9–3.2%/year until 2030 according to recent projections. By the end of the next decade, worldwide demand for natural gas is estimated to be about 2.2 billion cubic meters (bcm) per day [20].

Potential significant increase in NG supply to match the ever increasing demand necessitates decisions in all strategic, tactical, and operational levels in the process of building new and/or expanding existing NG networks. Indeed, many countries improve and expand their NG network to serve the increasing demand efficiently and in a cost effective manner. For instance, the Trans-Anatolian Gas Pipeline (TANAP) and the Trans Adriatic Pipeline (TAP) projects intend for the transportation of NG from Azerbaijan through Turkey to Europe. They offer the shortest link from the Caspian region to European markets with a competitive gas tariff. In both projects, capacities are planned to be increased via additions of pipelines and compressor stations over the coming years as the increases in supply and demand are realized. This effort, as any other with a similar objective, requires informed and justified decision-making to minimize the costs of investment and transporting gas through pipelines in multiple periods while increasing the customer service and offering reasonable price.

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NG is delivered to consumers through channels that consist of exploration, extraction, production, transmission, storage and distribution stages. Designing and operating an efficient and effective NG network is important to meet customers' demand on time and to minimize the costs especially in the transportation stages of transmission and distribution. An NG *transmission system* can be defined as a high-pressure pipeline system used to transport NG over long distances from suppliers to distribution centers with large diameter pipelines. An NG *distribution system* is a lower-pressure pipeline system that takes NG from the transmission system and delivers it to customers via small diameter pipelines.

In a typical NG *transmission network*, which is the focus of this study, main components include demand and supply nodes, pipelines, and compressor stations. In such complex and large networks, proper planning is important because even a small percentage reduction in investment and operation expenses provides considerable amounts of overall savings. We observe that, with the increasing demand, the size and the complexity of NG pipeline networks have also increased since transmission networks expand over time to meet demands at new consumer nodes. In turn, it is critical that the design and expansion decisions are made with careful consideration of their long term benefits since the networks are expected to be operational for long time periods and should be designed in order to satisfy varying needs over the planning horizon. A well-designed network helps NG companies minimize the strategic as well as the operational costs while increasing the customer service level.

The main thrust of this study is the development of a decision support tool to aid decision makers in optimizing NG transmission networks – to minimize the total investment and operating costs while satisfying certain requirements such as demand satisfaction and pressure limits in the system. In particular, we address NG transmission network design optimization in a multi-period setting and, to this end, propose a mixed integer nonlinear model (MINLP) to determine

1. the locations and capacities of compressor stations,
2. the pipelines to be used and/or installed,
3. the timing of pipeline and compressor station installations,
4. the amount of gas procurement from available suppliers, and
5. the gas pressure requirements and flows in the network

so as to minimize the sum of associated investment (installation of compressor stations and pipelines), operational (gas flow, compressor and pipeline operations), and gas procurement costs.

The main contribution of this study is to provide an integrated optimization model by considering components of planning decisions that are addressed separately in previous studies. Thus, the approach takes a holistic, overall system view to various components of NG transmission network design/expansion and provides a means to study the trade-offs involved to ultimately support a sound and well-founded decision making process. Using our model, we conduct several numerical experiments based on the NG network in Turkey to gain insights into sensitivity of network configuration and operations to the number of periods within the planning horizon and cost parameters as well as into the strategic decision making for design and expansion of natural gas networks. To this end, we illustrate the use of our approach in multiple experiments presented in Section 6.

The organization of the remainder of the paper is as follows. In Section 2, we provide a survey of previous related works. In Section 3, a general NG transmission system description along with its components and governing component-specific cost equations as well as parametric values are outlined. Then, we present the definition of our specific problem and its mathematical model for multi-period network design in Section 4. In Section 5, we provide the solution approach employed to solve the model, based on online optimization resources for MINLPs. In Section 6, based on realistic data utilizing the NG network structure in Turkey, we present extensive computational test results for varying instance sizes, planning period lengths and cost parameters. Finally, in Section 7, we state the conclusions and insights gained via this study for decision makers in the NG transmission network design and operation.

2. Related literature

In the literature, we observe that there are three main problem classes which address different challenges in NG transmission networks including

1. the design of NG networks with the purpose of minimizing investment costs for infrastructure (e.g., Kabirian and Hemmati [15], Hamedi et al. [14],
2. network expansion which addresses addition of new components to existing networks to address increasing demand (e.g., Chaudry et al. [6], Dieckhoner et al. [9], and
3. the network flows which aim to mainly minimize compressor energy usage while ensuring demand satisfaction at the operational level (e.g., Wong and Larson [23], Wu et al. [24], Borraz-Sanchez and Rios-Mercado [4], Rios-Mercado et al. [21], Uraikul et al. [22], Chebouba et al. [7]).

We emphasize that while the previous studies handle these NG network problems by using different models and approaches, in our study, we propose a generalized modeling and an optimization framework that can be instrumental in all of these areas separately or simultaneously depending on the input parameters. For example, the structure of a preexisting network can be assumed via fixing associated design variables and additional design variables can be utilized to make network expansion decisions. As another example, all of the design variables can be fixed to describe an existing network infrastructure, then the solution provides results on gas flow and procurement values to satisfy the expected demand.

In the design context, Kabirian and Hemmati [15] develop an integrated nonlinear optimization model for formulating a strategic plan to determine network components in a multi-period setting and utilize it for network expansion in a computational study. A heuristic random search optimization method is proposed to minimize the present value of operating and investment costs. In the work of Hamedi et al. [14], an operational distribution network problem to optimize gas flows in the network and to make decisions about distributor units' capacities and consumers' shortages. The objective is to minimize the costs of refinery, compressor station operations, storage and transmission. They propose a hierarchical algorithm to solve the single-objective, multi-period problem by using a MINLP model which is approximated as a MILP by adding a set of constraints.

In the expansion area, Chaudry et al. [6] develop a combined gas and electricity network model to determine the optimum network expansion policy in order to meet varying demand at lowest cost. The model is formulated as nonlinear mixed integer problem to minimize operational and infrastructure expansion costs in networks over the entire time horizon. Gas network expansion is implemented by varying the pipe diameters of existing pipes, adding additional compressor stations, and storage facilities. Dieckhoner et al. [9] provide a simulation-based study employing a variety of scenarios to analyze gas flows and potential congestion problems in European NG networks.