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# Optimal planning and infrastructure development for shale gas production

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ABSTRACT

Recently, there has been a significant interest to the development and exploitation of unconventional gas resources especially shale gas. Several places around the world have substantial shale gas reserves in regions that lack in the infrastructure needed for production and distribution. This paper presents a new mathematical programming approach based on disjunctive programming to account for complex logical relationships in the optimal planning of shale gas exploitation and infrastructure development in places without infrastructure for production, treatment, and distribution. Because of the variability in natural gas supplies and demands over time, a multi-period optimization approach is adopted over a certain time horizon, which includes Monte Carlo simulations to assess the associated volatility. The optimization approach accounts for the different components of the infrastructure, the production schedules, and the time-value of money to maximize the net present value of the infrastructure. The applicability of the proposed approach is shown through a case study in the Burgos basin located in the Northeast of Mexico and in the southern extension of the Maverick Basin in Texas. The results show attractive economic results for the exploitation and distribution of gas to satisfy the national demand.



## 1. Introduction

As a result of population growth and economic development, the energy consumption continues growing [1]. Important economic and environmental impacts for the increasing energy consumption have been identified [2]. According to recent estimates, the global energy consumption is projected to increase by 41% in two decades [3]. Therefore, there has been significant interest in emerging energy sources such as unconventional gas (shale gas, tight gas, coalbed methane gas) and renewable energy with the expectation that these resources will contribute significantly to the growing energy demands, as consequence it causes concerns about the potential adverse impacts [4]. The co-production of ethylene [5] has been analyzed to improve the profitability. The oil shale [6] can be used to produce liquid fuels via pyrolysis. Furthermore, the energy security has been widely studied [7]. In developing the supply chains of the emerging energy resources, optimization can provide the decision makers with powerful tools for strategic planning [8]. In this context, Gupta and Grossmann [9] presented an efficient strategic planning model for offshore oilfields. Santibañez-Aguilar et al. [10] developed an optimization model for planning supply chains associated with biofuels. Zhang et al. [11] proposed a multi-period mathematical programming model for the optimal planning of utility systems. For the specific case of shale gas production, planning must include the consideration for the use of substantial amounts of water used in hydraulic fracturing over a short period of time. Typically, 7500–49,000 $m^3$ of water are used to fracture each well [12]. Best and Lowry [13] quantified the potential effects due to the water extractions for the Marcellus shale play. Clark et al. [14] estimated the water consumption over the life cycle of a shale gas play. Furthermore, Vengosh et al. [15] presented a critical review about the associated risks in the shale gas operations. Yang et al. [16] developed a mixed-integer linear programming (MILP) model for the optimal planning of water use for shale gas production, and Lira-Barragán et al. [17] proposed a mathematical programing formulation for the optimal management of flowback water in shale gas production. Ikonnikova et al. [18] presented an evaluation for the profitability of a shale play. Kaiser [19] presented an economic analysis for the Haynesville shale play. Wejeimars [20] showed the importance of the geographical location for the shale gas production. Yuan et al. [21] reported a review for the shale gas production. Calderón et al. [22] incorporated financial aspects

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in the evaluation of the supply chain associated with the shale gas production. In spite of the usefulness of the aforementioned contributions, they have not accounted for the optimal planning for the shale gas production.

Regarding to the strategic planning and operation of shale gas fields, Rahman et al. [23] presented an optimization model for the hydraulic fracturing to establish relationships between treatment parameters and fracture growth while accounting for the return on investment. Knudsen et al. [24] proposed a Lagrangian relaxation-based approach for scheduling shut-in times in tight formation multi-well pads to stimulate the shale gas production in different wells. Cafaro and Grossmann [25] introduced a mixed-integer nonlinear programming (MINLP) model for the optimal planning in shale gas production to optimize the number of wells to drill at every location, the size of processing plants, the pipes, compression units and the amount of freshwater required for drilling a hydraulic fracturing. As well as He and You [26] developed three novel processes for integrating shale gas processing with ethylene production including an exergy analysis and the techno-economic analysis.

An important factor in developing a shale-gas production system is that there are many shale plays that are rich in gas reserves but very poor in infrastructure. Therefore, the strategic planning for the development of such areas requires careful scheduling and installation of the facilities needed for the wells in a multi-well pad to determine the operation startup time of the well according to the production time for the shale play and market demands. Furthermore, the size and startup time for the processing plant and the piping network (construction and operation startup time) for the raw gas distribution to the treatment process will be determined. Additionally, the scheduling for the construction and sizing of the network from the processing gas units to the market must be accounted for. Therefore, the goal of this work is to propose a new optimization approach for designing the entire infrastructure from shale gas resources (for places without infrastructure) to maximize the net present value (NPV) of the entire supply chain given the demand of natural gas in the market under study while addressing the following issues: (1) Determining the number of wells drilling and operating in a certain multi-well pad in a given time period. (2) Scheduling the drilling to generate an optimal planning for each source. (3) Predict the drop in the profile production of the wells. (4) Planning the shale gas production in the play over the time periods while accounting for the changes to the demand through the time. (5) Determining the gas-processing plant capacity as well as the operation startup time for the shale gas play production. (6) Designing and operating the transmission network over the time while accounting for the construction and startup times. (7) Considering the long-term capital and the operating costs for the project.

## 2. Problem statement

Consider a shale gas play without the production and distribution infrastructure. The objective is to determine the optimal planning and scheduling for developing the infrastructure for shale gas production and distribution while accounting for market demands, the development of wells, the construction of gas-processing plants and the distribution of the raw and the processed gas. Because of the planning aspects of the problem, there is a need to account for the capacity expansion of the considered units over a time horizon. Fig. 1 shows schematically the addressed problem for the strategic planning of shale gas production in places without infrastructure. The addressed problem can be formally stated as follows:

Given is a set of potential multi-well pads in the same geographical shale formation with a specific number of wells ($i = \{i|i = 1,2, \ldots, N_n\}$). The wells are characterized with a specific volume of the raw gas and the physical properties of the source that are determined for the dense rock formation to provide a particular composition in each well. Given also are the time periods ($t = \{t|t = 1,2, \ldots, N_n\}$, which set the long-term problem in years. The market zone distribution are described by the set ($m = \{m|m = 1,2, \ldots, N_n\}$), where the produced natural gas is supplied. Each market is associated with a defined demand, which is determined by the natural gas consumption for the different customers in the market zones. A set of potential processing plants is given also ($p = \{p|p = 1,2, \ldots, N_n\}$), where the capacity depends on the well production. Every processing plant is characterized through performance parameters that are related to the capital cost function and a maximum allowable processing capacity. The transmission cost for the gas produced in the shale play to the processing plant is defined by the rate of gas extracted from each well, the size for the pipes, and the energy required in the compression units. Additionally, the unit piping and pumping costs for the distribution network are given along with the geographical routes over which the distribution network may be constructed.

The objective is to develop a mathematical programming approach to determine the optimal infrastructure, configuration, and production schemes for the production of natural gas using hydraulic fracturing, gas treatment plants and distribution network of natural gas for a specific time horizon. The objective function is the maximization of the net present value for the profit (*NPVPROFIT*), which includes the total sales in all markets over all the time periods of the considered time horizon, the total capital cost involved in the installation of the production network (*TOTCAPPC*) and the total operating cost associated with the network (*TOTOPCOST*).

To solve the addressed problem, a superstructure is first developed as shown in Fig. 2. It consists of potential wells, gas treatment plants, and distribution networks. To determine the optimal planning and scheduling for the natural gas production from the shale gas plays in places without infrastructure, there is a need to properly account for the operating and capital costs associated with the supply chain, as well as the economic factors over the considered time horizon. There is also a need to obtain information on the shale play formation, the maximum potential capacity of each well, and the geographical system including the possible routes for the distribution pipeline network and the consumption markets. The next section describes the optimization formulation used to address the problem.

## 3. Optimization model

In formulating the optimization problem, several indices are used: $i$ represents the wells, $p$ describes the multi-well-pads, $m$ refers to the markets, $r$ designates the processing plants/compression units, $s$ denotes storage units. Furthermore, the index $t$ is used to define the time periods over the given horizon. The detailed nomenclature is presented in the electronic supplementary material.

### *3.1. Balance in wells*

The gas produced in each well over a given time period ($f_{i,p,t}^{well}$) can be distributed to any processing plant ($f_{i,p,r,t}$):

$$f_{i,p,t}^{well} = \sum_{r} f_{i,p,r,t}, \quad \forall i, p, t \tag{1}$$

### *3.2. Balance in the inlet of processing plant/compression unit*

The total gas inlet to the processing plants/compression units ($f_{r,t}^{in\text{-}pc}$) is equal to the sum of the production of the wells over a given time period ($f_{i,p,r,t}$):