

On the impacts of flow reversals in the optimal design and operation of pipeline networks

Renzo O. Piccoli^{1,2}, Diego J. Trucco³, Demian J. Presser^{1,3}, Diego C. Cafaro^{1,3}

¹ INTEC (UNL-CONICET), Güemes 3450, 3000 Santa Fe, Argentina

² Facultad Regional Santa Fe, Universidad Tecnológica Nacional, Lavaisse 610, 3000 Santa Fe, Argentina

³ Facultad de Ingeniería Química, Universidad Nacional del Litoral, Santiago del Estero 2829, 3000 Santa Fe, Argentina

rpiccoli@frsf.utn.edu.ar

Abstract. The transportation of fluid products across extensive supply chains is usually made by pipelines. Large investment costs in pipelines are only justified if they operate steadily at high utilization levels over long periods of time. That is why building efficient pipeline networks has become a challenging task. One of the most interesting strategies that pipeline operators apply after an abrupt change in the production-demand balance is flow reversal. Reversing the flow of a pipeline segment aims at using the same transportation infrastructure to make products flow in the opposite direction, which can be particularly useful to reduce costs. This work makes use of a generalized optimization framework based on Mixed-Integer Nonlinear Programming (MINLP) models for the design and operation of pipeline networks, to assess the impact of flow reversals. The goal is to optimally connect the nodes and install facilities to gather production and make the products be ready for delivery. Flow direction may be reversed in any pipeline segment over time, but in contrast to previous contributions, changeover costs and additional capital and operational expenditures due to specific pieces of equipment are explicitly accounted for.

Keywords. Pipeline Network, Optimization, Shale Gas, Flow Reversal.

1 Introduction

Unconventional oil and gas reserves have become strategic energy sources for several countries. They also serve as raw materials for a significant number of industrial products. Onshore oil and gas fields typically consist of a set of wells geographically distributed within the exploitation area. Oil and gas extraction usually involves expensive materials and equipment, including production assets, pipelines and processing facilities. Pipelines, in particular, are a highly efficient mean of transportation for liquid and gas products across oil and gas fields. However, the construction of pipeline networks entails significant investment costs, which are only justified if they are operated at high

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utilization levels in the long term. As production and demand patterns for most industries are changing fast, often under uncertain and unforeseen circumstances, building efficient pipeline networks has become an increasingly relevant challenge.

In this work, we aim to introduce new concepts and tools that support decision-making when designing a pipeline network for the upstream sector of petrochemical industries, seeking to optimize resource utilization and reduce associated costs. We make use of a generalized optimization framework that assumes no predetermined number of echelons (subsequent segments connecting a source and a sink node) and also allows for flow reversals in any pipeline segment over the time horizon. In contrast to previous contributions, capital and operational expenditures due to specific pieces of equipment are explicitly accounted for. The optimization model is focused on shale gas production and consists of two main parts: topological and fluid dynamics constraints. On the one hand, the optimal topology of the pipeline network is determined using 0-1 variables, which account for the installation of pipeline segments of specific diameters, selected from a set of alternatives. Based on the pipeline dimensions, quadratic fluid dynamics correlations permit to calculate pressure drops, which are functions of gas flow rates and inlet pressures.

Considering pressures as decision variables enables the optimization of flow rates and directions, effectively increasing the utilization of the transportation capacity. Nevertheless, in the event of a pipeline flow reversal, it becomes imperative to manage the sign of the pressure difference, thereby creating disjunctive representations of material flow constraints for each time period. All these components yield a mixed-integer quadratically constrained programming (MIQCP) formulation of combinatorial complexity. To solve the problem to global optimality, decomposition strategies and tightening algorithms have been proposed in the literature, systematically adding fluid dynamic constraints to a reduced set of segments and directions in the network.

The novel aspect of this work is the optimal management of flow reversals. Reversible pipelines can be particularly useful to achieve more economical network designs. Interesting examples of flow reversals are shown in gas primary production, where highly integrated pipeline networks are built and operated to move natural gas from wells to separation facilities. In a real context, the focus of companies in oil or gas operations often changes over time, usually driven by productivity and prices, yielding the mobilization of rigs and fracturing equipment from one region to another. However, centralized processing facilities and pipeline networks can hardly ever be relocated. This implies that gas flows may be subject to reversals if the same pipelines are used to send production streams in the opposite direction, under alternating development strategies. Despite being a relevant problem, the active implementation of flow reversals has not been formally addressed in the optimal design and operation of pipeline networks. In fact, none of the previous works have assessed to what extent the complexity of flow reversals is justified. Converting a pipeline segment into a bidirectional transportation resource requires large capital investment in additional equipment, namely pumps, compressors, valves and manifolds. Moreover, every time the pipeline flow direction changes from direct to reverse mode, time- and cost-consuming tasks need to be performed. In previous works dealing with water networks, flow reversal was employed

with no additional cost, due to its relatively minor importance when compared to pipeline investment. However, flow reversals costs are particularly relevant in gas pipeline networks.

The aim of this work is to develop an optimization model to design the network of pipelines and processing facilities for shale gas production, accounting for flow reversals. The model seeks to maximize utilization of pipeline segments and facilities in order to reduce costs. Critical aspects such as changing rates and composition, starting times of production at each wellpad, transport and processing capacities, among others, will be considered.

In the next sections we thoroughly revise previous contributions to the field and then formally define the problem together with the model assumptions. Afterwards we present the optimization model and finally solve a case study of real dimensions to assess the potential of flow reversals and draw conclusions.

1.1 Literature review

The research community has been increasingly focused on the optimal design, planning, and operation of pipeline networks for more than 40 years. Extensive research has been conducted, employing diverse methodologies. However, a notable drawback in much of this literature is to omit significant changes in oil and gas production rates along the lifetime of the wells. Mah and Shacham (1978) made one of the earliest contributions to the field, presenting network elements, characterizing typical flows, while also introducing alternative formulations for the optimization problem. Their work also offered insightful analogies with electrical circuits and proposed various methods for solving nonlinear problems. Similarly, Duran and Grossmann (1986) tackled the design complexities of supply networks for natural gas production and marketing, through MINLP formulations. To confront the computational challenges inherent in solving such formulations, they suggested different solution strategies, including piecewise linear approximations and other linearization techniques, underscoring the intricate nature of designing pipeline networks alongside facility planning decisions.

In recent years, attention has focused towards optimizing gathering networks for unconventional gas production. Cafaro and Grossmann (2014) conducted one of the earliest studies in this domain, proposing a non-convex MINLP formulation to optimize drilling operations over shale gas areas. Their approach simultaneously determines the optimal location and size of compressors, pipelines, and gas processing plants. Concurrently, other researchers have endeavored to develop more comprehensive models that account for greater details of pipeline operations, as exemplified by Drouven and Grossmann (2016). Furthermore, Zhang et al. (2017) introduced an optimization framework in for oil and gas networks aimed at minimizing investment costs. Their model considered specific connectivity structures and pressure drop limits, managing friction losses and differences of elevation by means of simplified linear equations. Other studies, such as Guerra et al. (2019), proposed a general methodology for integrated planning of shale gas and water infrastructure under uncertainty. The authors developed a two-stage stochastic model considering key uncertain parameters in the problem to be solved.

Regarding fluid dynamics, the work of Drouven and Grossmann (2017) determines the linear pressure profile within a shale gas collection network and the power required by compressors. In turn, Liu et al. (2020) studied the optimization of natural gas pipeline networks, considering uncertainties in demand and production composition. They propose a robust optimization algorithm with rigorous thermodynamic equations, calculating pressures at each node in the network. Hong et al. (2019) focused on pipeline network design with detailed attention to hydraulic aspects, which had been overlooked by previous studies. Their work proposed a Mixed-Integer Linear Programming (MILP) formulation to minimize total costs while considering technological constraints, terrain profiles, commercial pipeline diameters, and pressures in all the circuit. Then, Hong et al. (2020) updated their work addressing the optimal design of a pipeline system for shale gas production using a piecewise linear approximation of pressure drops based on discrete ranges of flow rates. They solved the problem using an ant colony algorithm that predefines the set of potential connections. In alignment with prior research, Dbouk et al. (2020) proposed an optimization model emphasizing topological complexities and leveraging the shortest path algorithm as a solution heuristic. However, all these approaches overlook unconventional production, offering static formulations that fail to consider production decline and the continuous incorporation of new wells over the planning horizon. Other works, like Montagna et al. (2021), propose an MINLP model for optimizing the design of a pipeline network that connects shale oil wells to tank batteries. The model takes into account detailed calculations of multiphase pressure drops to determine pipeline diameters based on product flows over time. Their approach helps to ensure that the pipeline system can handle the expected production volumes and reduce the risk of operational issues.

Cafaro and Grossmann (2020) introduced the possibility of employing bidirectional pipeline segments in water pipeline networks. The results indicate a significant benefit when flow reversals are implemented in the network design, allowing for the supply, collection, treatment, and recycling of water streams. In unconventional exploitation areas, nodes with high water demand transition to production nodes after a few months, needing a change in flow direction to effectively collect and process water, referred to as "flowback." Other examples of flow reversals in industrial pipeline networks include hydrogen, methane, and carbon dioxide transportation. More recently, Montagna et al. (2022) presented a new model that addresses combined shale oil and gas development strategies. This model can be considered an extension of the previous contributions by the same research group, being not limited to a determined number of echelons to build the network, also allowing for flow reversals.

2 Problem Definition

The problem addressed in this work involves the design of the network of pipelines and surface facilities to process shale gas production from multiple wellpads over a long-term planning horizon. The aim is to minimize the total present cost (TPC) of the project under alternative development strategies. The development plan is given beforehand,

which has been previously forecasted based on gas price scenarios. Input data also include the expected productivity profiles over time and the fluid dynamics characteristics of the gases. The main objective is to determine the optimal number, location, and size of processing facilities, as well as the pipeline network (including pipeline diameters and lengths) to efficiently transport and process shale gas from the unconventional formation, accounting for the possibility of flow reversals between nodes at different time periods.

Thus, establishing the network of pipelines for transporting shale gas in this industrial sector involves a series of decisions, namely: (a) determining connections between nodes (arcs or segments), (b) selecting the diameter of each pipeline required for each segment, and (c) managing the flows along each pipeline within the specified time horizon. The time frame is typically discretized into months or bimesters (Saldanha-da-Gama, 2018). Potential locations of processing facilities are predetermined; typically, all nodes (wellpads) are considered potential sites for facility installation.

Although shale oil and shale gas are usually produced together from the same well, this work is only focused on shale gas flows, for simplicity. The aim of this work is to assess the benefits of flow reversals, showing how to optimally manage fluid dynamics across the pipeline network. The process of designing a pipeline network to transport gas involves three primary decisions. First, how to connect the nodes, i.e., determining the pipeline layout. Second, determining the required diameter for each segment. And third, identifying the flow direction and transportation rate along each pipeline segment during the time horizon.

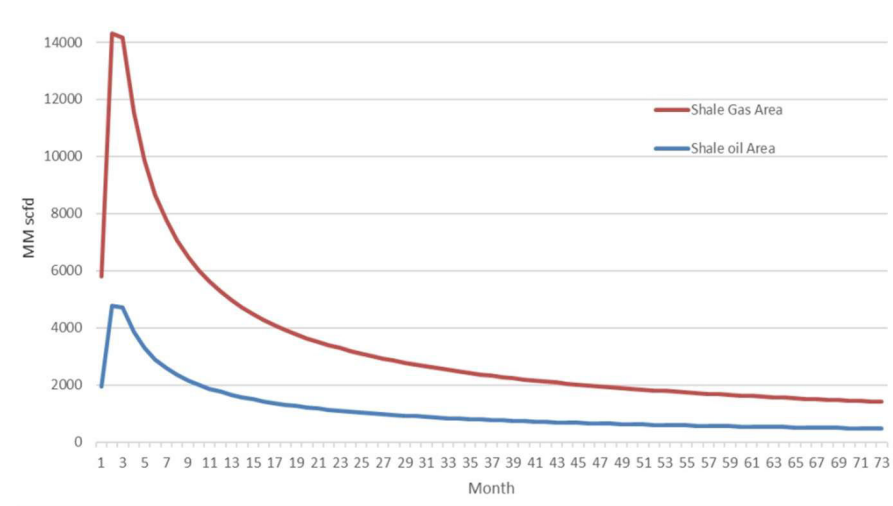


Fig. 1. Characteristic curves of shale gas production in (a) a gas area, (b) an oil area

The location of production sources, the length of each possible connection, and the gas production profiles (Fig.1) in a specific region are given. However, deciding whether or not to build a pipeline to connect a pair of nodes is a decision that needs to be optimally made. As it has been already explained, the network may have any number of echelons in any path, and the flow direction may be reversed in any pipeline segment over the time horizon. We assume that there are different commercial diameters to consider for the design, as well as different processing plant capacities for the shale gas. These are decision variables that seek for the optimization of pipeline network costs, taking into account constraints from the fluid dynamics of the shale gas transportation.

3 Model Assumptions

1. The development of wells is organized in rows of wellpads (Fig 2). This arrangement maximizes the recovery of resources from the shale formation by intensively drilling and fracturing horizontal wells in a compact area, also minimizing resource mobilization (Ondeck et al. 2019). The geographical location of the wellpads to develop is given.
2. The production to be considered in the region is only shale gas according to given production profiles.
3. There is a finite set of alternative sizes and processing capacities for facilities.
4. The gas flow that departs from a wellpad travels through a flowline and reaches the appropriate collecting node in the row.
5. The pressure of shale gas flows can only be boosted at the wellpads.
6. Every row is a potential location for junction and/or processing facility.
7. All connections between nodes are free to let the flow run in one direction or another in each period.
8. A development plan for shale gas wells is given beforehand and includes:
 - a. Number of wells to develop in each wellpad.
 - b. Drilling and completion dates of the wells in the pad.
 - c. Productivity of gas for every wellpad over the time horizon.

Characteristic shale wells are horizontally drilled and typically distributed as shown in Fig. 2. Rectangles depicted in that figure correspond to different rows of wellpads with horizontally drilled wells. Additionally, potential interconnections between these rows, where pipelines of different diameters can be installed, are indicated by gray dotted lines. All possible connections between different nodes allow for reversible flow, meaning that the direction can be changed on a period-by-period fashion.

Considering the equations governing compressible fluid transportation through the network, a mixed-integer quadratic programming (MIQCP) formulation can be developed. Based on previous contributions (Presser et al., 2023), support will be sought for solving the problem using decomposition strategies and progressively tightening algorithms.

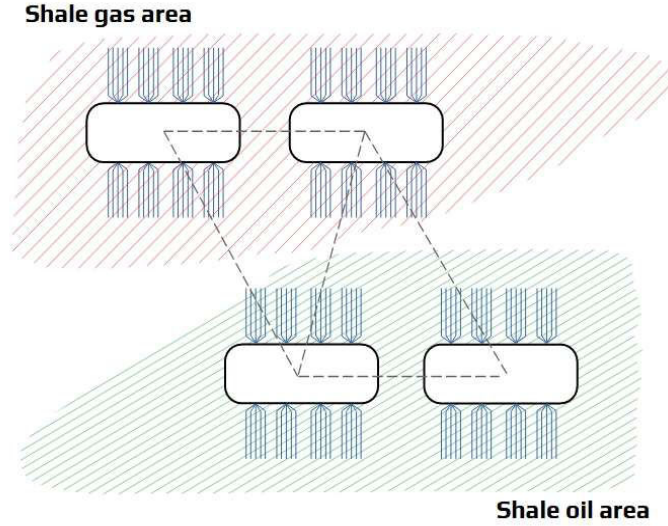


Fig. 2. Wellpads, rows and possible connections

4 Mathematical formulation

In this section, a Mixed Integer Quadratically Constrained Program (MIQCP) is presented with the aim of obtaining the optimal pipeline and surface facility network for shale gas gathering and processing.

Let $r \in R$ be the set of rows that constitute the shale gas exploitation area and $t \in T$ be the set of intervals used for time discretization. The parameter $p_{r,t}$ represents the production forecast for the row r during the time interval t . The variable $P_{r,t}$ represents the gas quantity processed at the surface facility in row r , if any. The set $J_{r,r'}$ includes the potential connections between rows r and r' , while $Q_{r,r',t}$ is the positive variable that indicates the amount of gas sent from row r to row r' in time interval t .

Equation (1) represents the mass balance for row r over time period t . The quantity produced or transferred into the row must either be sent to another row r' or be processed. It is worth noting that the production flows are gathered in their way to the row equipped with a processing facility.

$$p_{r,t} + \sum_{r' \in J_{r,r'}} Q_{r',r,t} = P_{r,t} + \sum_{r' \in J_{r,r'}} Q_{r,r',t} \quad \forall r, t \quad (1)$$

In addition, Eq. (2) implies that all shale gas produced during time interval t must be processed within the same period, with no possibility of storing raw gas in this model.

$$\sum_r P_{r,t} = \sum_r p_{r,t} \quad \forall t \quad (2)$$

The overall capacity of the processing facilities already installed in row r is imposed as an upper bound for $P_{r,t}$ in Eq. (3). The subset TI includes the time periods t where the company can invest in processing facilities, pipeline connections or flow reversal

capability. The set $s \in S$ comprises the various sizes of processing facilities considered, with the parameter pc_s indicating the processing capacity for size s . The binary variable $y_{r,s,t}$ denotes the decision to install a new facility of size s in row r during time period t .

$$P_{r,t} \leq \sum_{t' \in TI \mid t' \leq t} \sum_s (pc_s \cdot y_{r,s,t'}) \quad \forall r, t \quad (3)$$

We also define the set $d \in D$ to account for the pipeline diameters that are available. To incorporate the flow reversal feature in this model we introduce the binary variable $x_{r,r',d,t}$ that equals one if a pipeline with diameter d is installed between rows r and r' at time period t , while the binary variable $x_{dir_{r,r'},t}$ takes value one if the flow direction over time period t is from row r to row r' .

Eq. (4) specifies that the direction between rows r and r' during period t can be assigned a value of one only if a pipeline was previously installed for that connection. The fact that two opposite directions cannot be operating simultaneously for a given connection (r, r') is taken into account in Eq. (5). Additionally, Eq. (6) determines the pipeline flow capacity for a connection (r, r') over time period t , depending on whether that direction is taken. The positive variable $MaxFlow_{r,r',d,t}$ denotes the maximum admissible flow rate through a pipeline of diameter d connecting row r to r' . The scalar $MaxP$ represents the peak production of the entire development plan and serves as an upper bound.

$$x_{dir_{r,r'},t} \leq \sum_{t' \in TI \mid t' \leq t} \sum_d (x_{r,r',d,t'} + x_{r',r,d,t'}) \quad \forall (r, r') \in J_{r,r'}, t \quad (4)$$

$$x_{dir_{r,r'},t} + x_{dir_{r',r},t} \leq 1 \quad \forall (r, r') \in J_{r,r'}, t \quad (5)$$

$$MaxFlow_{r,r',d,t} \leq MaxP \cdot x_{dir_{r,r'},t} \quad \forall (r, r') \in J_{r,r'}, d, t \quad (6)$$

Eq. (7) restricts that only a single pipeline segment can be installed between a pair of nodes. This prevents the model to carry out parallel installations, with the same or opposite directions.

$$\sum_{t' \in TI \mid t' \leq t} \sum_d x_{r,r',d,t'} \leq 1 \quad \forall (r, r') \in J_{r,r'}, t \quad (7)$$

Equations (8) and (9) model the flow reversal feature, which allows changing the flow direction over a segment at a specific point in time. $v_{r,r',t}$ is the binary variable that indicates a change in the pipeline flow direction from (r', r) to (r, r') at period t , while the binary variable $w_{r,r',t}$ takes a value of one if the equipment necessary for the flow reversal in pipeline connection (r, r') has been installed during a previous time period. Both the installation and the utilization of this equipment involve specific costs, namely ifr and ofr respectively.

$$v_{r,r',t} \geq x_{dir_{r,r'},t} - x_{dir_{r,r'},t-1} - \sum_{t' \in TI \mid t' \leq t} \sum_d (x_{r,r',d,t'} + x_{r',r,d,t'}) \quad (8)$$

$$v_{r,r',t} \leq \sum_{t' \in TI \mid t' \leq t} (w_{r,r',t'} + w_{r',r,t'}) \quad \forall (r, r') \in J_{r,r'}, t \quad (9)$$

To address the issue of modelling gas fluid-dynamics in this study, the Weymouth correlation (Weymouth, 1912) is used. This correlation is well-suited for designing pipelines in gas field gathering systems, as noted by Montagna et al. (2022). A simplified version of the correlation is presented in Eq. (10) for a given pipeline length and temperature.

$$F = \frac{1.1 \cdot d^{2.667}}{l \cdot s \cdot z \cdot T_1} \cdot (P_1^2 - P_2^2)^{0.5} \leftrightarrow F^2 = \varphi^2 \cdot d^{5.334} \cdot (P_1^2 - P_2^2) \quad (10)$$

F is the gas flow rate in million standard cubic feet per day (10^6 scf/day or MMscfd), d and l are the pipeline inside diameter (in inches), is the length (in feet), s is the specific gravity of the gas in normal conditions (relative to air), z is the gas compressibility factor, T_1 is the temperature of the gas inlet (in °R), while P_1 and P_2 are the inlet and outlet absolute pressures (in psi). The parameter φ synthetizes all the factors that are assumed to be constant for a given pipeline segment and is also employed for unit conversion.

Based on the previous equation, we can incorporate the following set of constraints into the model. The non-negative variable $P_{r,t}^{sq}$ specifies the square pressure at the junction of row r during time period t , for unprocessed shale gas transportation, meanwhile $\Delta P_{r,r',t}^{sq}$ refers to the difference of square pressures between two adjacent rows r and r' . In Eq. (11) the maximum admissible flow rate through a pipeline of diameter d connecting r to r' ($MaxFlow_{r,r',d,t}$) is determined. Note that $diam_d$ is a model parameter typically given in inches. As $MaxFlow_{r,r',d,t}$ is non-negative, it can be squared, resulting in a quadratic constraint.

$$MaxFlow_{r,r',d,t}^2 \leq \varphi^2 \cdot diam_d^{5.334} \cdot \Delta P_{r,r',t}^{sq} \quad \forall (r, r') \in J_{r,r'}, d, t \quad (11)$$

$$\Delta P_{r,r',t}^{sq} \leq (P_{r,t}^{sq} - P_{r',t}^{sq}) + \Delta sp_{r,r'}^{max} \cdot (1 - x_{dir_{r,r',t}}) \quad \forall (r, r') \in J_{r,r'}, t \quad (12)$$

$$\Delta P_{r,r',t}^{sq} \leq \Delta sp_{r,r'}^{max} \cdot x_{dir_{r,r',t}} \quad \forall (r, r') \in J_{r,r'}, t \quad (13)$$

$$Q_{r,r',t} \leq \sum_d MaxFlow_{r,r',d,t} \quad \forall (r, r') \in J_{r,r'}, t \quad (14)$$

$$MaxFlow_{r,r',d,t} \leq fmax \cdot \sum_{t' \in T | t' \leq t} (x_{r,r',d,t'} + x_{r',r,d,t'}) \quad \forall (r, r') \in J_{r,r'}, d, t \quad (15)$$

Note that as pipeline flows can be reversed, it is necessary to enforce the flow to be zero when the difference of square pressures is negative, indicating that the gas is moving in the opposite direction. This constraint is imposed by equations (12) and (13). $\Delta sp_{r,r'}^{max}$ is the maximum difference of square pressures for gas pipeline segments and is typically determined by the difference between the square pressure at the wellheads and the square of the minimum pressure required at the inlet of a gas processing facility. Finally, constraints (14) and (15) limit the maximum flowrate according to the diameter of the pipeline installed between the nodes r and r' .

To limit the working pressures in each node we establish lower and upper bounds for them. Such values are given by the magnitude of the pressure at the outlet of the wells

(upper bound, p_{max}) and the minimum pressure required in the processing facilities to operate (lower bound, p_{min}). Eq. (16) and Eq. (17) below reflect such restrictions.

$$P_{r,t}^{sq} \geq p_{min}^2 \quad \forall r, t \quad (16)$$

$$P_{r,t}^{sq} \leq p_{max}^2 \quad \forall r, t \quad (17)$$

The model seeks to minimize the total present cost TPC of the facilities (including pipelines) that are required to gather, process and deliver the flows over the time horizon. Such an objective function is given by Eq. (18), where i is the interest rate to discount cashflows back to present, and ipf_s and $ipl_{d,r,r'}$ are fixed investment costs for processing facilities and pipelines.

$$Min TPC = \sum_t \frac{1}{(1+i)^{t-1}} \left[\sum_{r,s} (ipf_s \cdot y_{r,s,t}) + \sum_{r,r',d} (ipl_{d,r,r'} \cdot x_{r,r',d,t}) + \right. \\ \left. \sum_{r,r'} (ifr \cdot w_{r,r',t}) + \sum_{r,r'} (ofr \cdot v_{r,r',t}) \right] \quad (18)$$

In summary, the MIQCP model for the optimal design of gas gathering networks aims to minimize the objective function (18), subject to constraints (1) to (9), and (11) to (17). Redundant constraints can be also added to speed up model resolution (typically called integer cuts). Note that only one set of constraints in the model, Eq. (11), is non-linear (quadratic). However, it is important to highlight that the MIQCP formulation yielded is convex.

The problem at hand is notably challenging due to the need of monitoring the pressures at the rows connections. The intricate nature of modeling gas fluid dynamics contributes to the complexity of this problem, which results in an increase of the computational time required for its resolution.

5 Solution algorithm

Modeling dynamics of gas flows through the network yields a challenging non-linear (quadratic) formulation. Tackling this problem monolithically results in long computation times or intractable problems, especially when the superstructure is large. To address these challenges, we make use of an efficient algorithm that iterates between relaxed and feasible solutions, solving models with fewer quadratic equations and binary variables than the original problem. This algorithm has been originally proposed by Presser et al. (2023) and guarantees global optimal solutions in a finite number of iterations. Moreover, it can be used to obtain good quality solutions in reasonable times, avoiding unnecessary constraints and reducing the overall time.

The first step involves solving a relaxed MILP problem with the assumption that the flow in every connection is not restricted by pressure drop constraints. The solution will seek to minimize the total length of pipeline segments installed, paying the cost of the smallest possible diameter.

In the second step, linearized pressure constraints are imposed only on the segments and directions of the previous network topology, and a second relaxed MILP problem is solved. In the third step, if a connection that has been previously selected is used to

build the network for the second time (i.e., linear pressure restrictions have been already imposed), the proper quadratic constraints are stated on that connection, from that point on. Thus, a tighter MIQCP problem is tackled.

This process is repeated iteratively until the pressure constraints for the original problem are satisfied by all the pipeline segments and directions selected in the network topology. Each solution obtained from the relaxed problems provides a valid lower bound for the main problem.

In parallel, and subsequent to the resolution of a relaxation, a feasible solution can be generated by restricting the pipeline connections to those selected and enabling the flow reversal feature only in those segments where it has been already tried. Then, the only remaining task is to determine the diameter of the selected connections. This feasible solution serves as an upper bound for the original problem. In case global optimality is not the objective, the algorithm can be stopped when the difference between the lower and upper bound falls below a specified threshold.

6 Case study and results

An illustrative case study of realistic dimensions is proposed as a mean of validating the optimization model. The example consists of eight rows of wellpads to be developed in the next six years. Possible connections between rows can be seen in Fig. 3. The production plan has already been established for each sector and row. Time horizon is discretized in bimonthly periods.

There are five alternative pipeline diameters to be used for gas flows: 10, 12, 16, 20 and 24 inches. The cost of the pipelines is set at 45,000 USD per inch of diameter and km of length. There are three alternative sizes for gas processing facilities: 128, 256, and 625 MMscfd, whose costs are: 115, 200, 435 thousand USD, respectively. The cost for the installation of equipment and accessories to add the flow reversal feature in a pipeline segment is set at 500,000 USD, and each time the flow is reversed a total operating cost of 50,000 USD should be paid. For simplicity, capital and operating cost for reversals are independent of the segment length and diameter. The annual interest rate has been fixed at 25%. The case study is implemented on GAMS 36.1 and solved using Gurobi library version 9.5, on an Intel Core i5-8265U CPU with 8 GB RAM, with 4 parallel threads.

With the parameters specified, we have solved the model utilizing the proposed algorithm until achieving global optimality. The time required for computation amounts to 89,510 [s], resulting in a TPC of 422.0 [MMUSD]. The final solution is depicted in Fig. 4, while the corresponding investments plans for pipelines and processing facilities are presented in Tables 1 and 2, respectively.

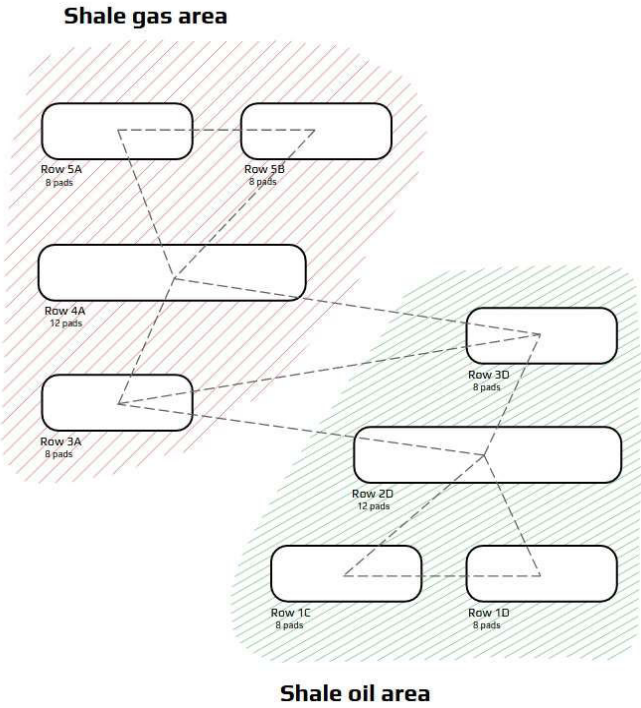


Fig. 3. Case study comprising a shale gas area and a shale oil area with 4 rows each.

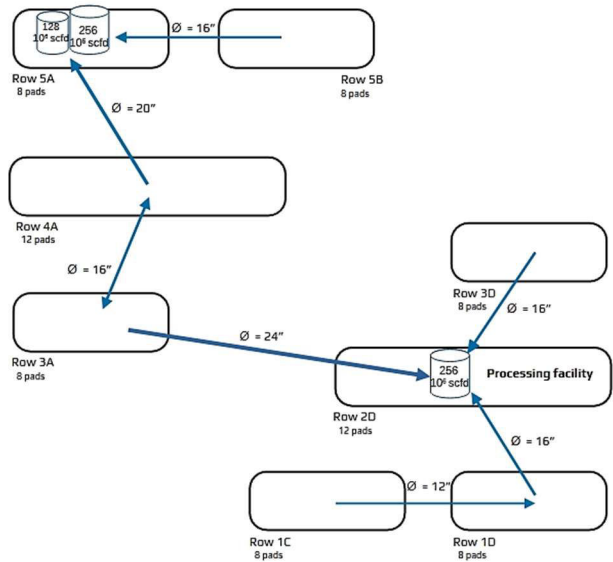


Fig. 4. Optimal solution for case study found by the MIQCP model

Table 1. Pipelines investment plan for the optimal solution

| Sector Row <i>r</i> | Sector Row <i>r'</i> | Diameter [in] | Time period [Bimester] |
|---------------------|----------------------|---------------|------------------------|
| 1C | 1D | 12 | 1 |
| 1D | 2D | 16 | 1 |
| 3D | 2D | 16 | 13 |
| 3A | 2D | 24 | 19 |
| 3A | 4A | 16 | 19 |
| 4A | 5A | 20 | 19 |
| 5B | 5A | 16 | 31 |

Table 2. Processing facilities investment plan for the optimal solution

| | Facility size [10 ⁶ scfd] | Time period [Bimester] |
|----|--------------------------------------|------------------------|
| 2D | 256 | 1 |
| 5A | 256 | 19 |
| 5A | 128 | 25 |

The flow reversal feature has been suggested for one of the segments of the resulting gas network, as shown in Fig. 4. To investigate the impact of this decision, a comparative analysis is conducted by running the same optimization problem without reversals, which implies a reduction in the computational burden but also an increase in total costs. The TPC for this problem results in 423.2 [MMUSD], i.e. an increase of 1.2 [MMUSD]. Although the overall pipeline length and network structure are quite similar (see Fig.5), a significant increase in pipeline diameters is observed. Savings favored by flow reversals are a direct consequence of the improved utilization of available resources, particularly the pipeline segment between rows 3A and 4A.

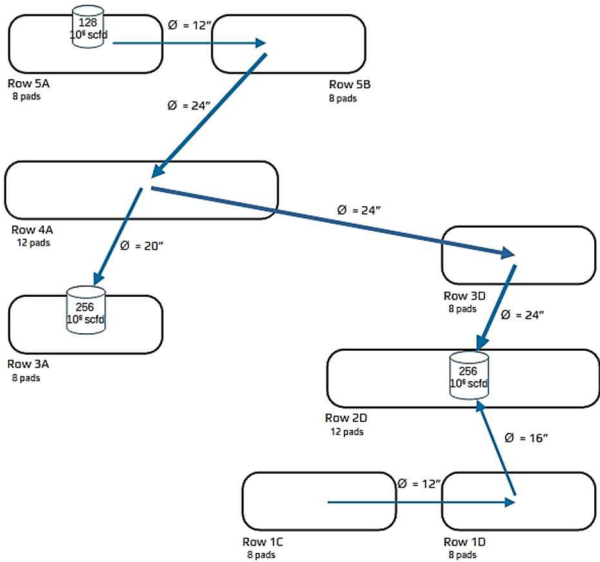


Fig. 5. Optimal solution found without the flow reversal feature

The effectiveness of pipeline reversals is further illustrated by tracking flowrate and pressures along the bidirectional segment 3A-4A in Fig. 6. In that figure, the gray area represents the actual transportation capacity, and the solid line represents the shale gas flow, over the bimesters.

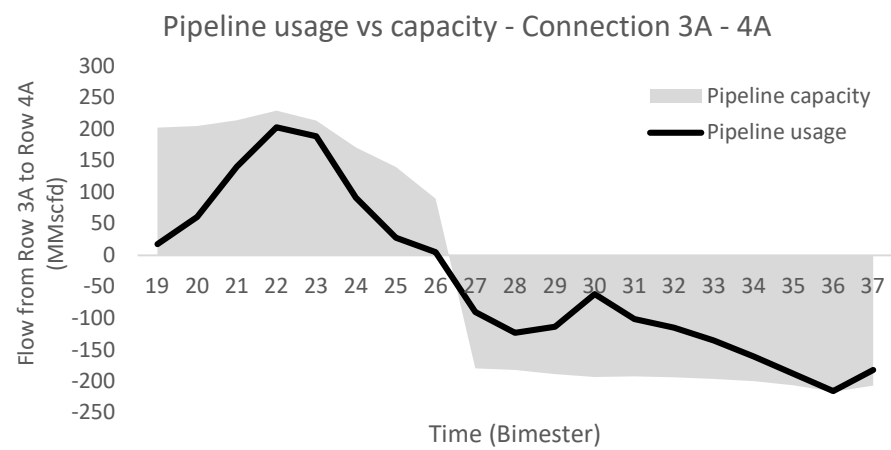


Fig. 6. Pipeline segment 3A-4A utilization in contrast with capacity

Table 3. Model statistics for each iteration of the algorithm

| Iteration | Compu- tational time [s] | Accumu- lated time [s] | Number of equa- tions | Number of varia- bles | Number of binary variables | Relaxed TPC | Feasible TPC |
|-----------|--------------------------------|------------------------------|-----------------------------|-----------------------------|----------------------------------|----------------|-----------------|
| 1* | 10 | 10 | 14505 | 13924 | 5844 | 406.74 | 434.52 |
| 2* | 190 | 200 | 16318 | 14183 | 5844 | 408.46 | 423.19 |
| 3* | 370 | 570 | 17872 | 14405 | 5844 | 411.36 | 422.08 |
| 4 | 1805 | 2375 | 18649 | 14516 | 5844 | 414.21 | 422.42 |
| 5 | 3785 | 6160 | 19685 | 14664 | 5844 | 419.37 | 423.92 |
| 6 | 8725 | 14885 | 19944 | 14701 | 5844 | 420.03 | 423.19 |
| 7* | 38825 | 53710 | 20203 | 14738 | 5844 | 421.75 | 421.99 |
| 8 | 35800 | 89510 | 23548 | 15054 | 5844 | 421.75 | 421.75 |

*New best solution found

Table 3 displays the statistical data for every iteration of the solution algorithm. It is noteworthy that the number of equations and variables progressively increases with each iteration, as additional pressure drop constraints are included, leading to longer computational times. It is also important to mention that if we were not aiming for guaranteed global optimality, the algorithm could have been stopped at iteration 7 as the lower and upper bounds are already very close (0.06%). The feasible solution obtained at iteration 7 is also the global optimal solution. However, to verify optimality, an additional iteration requiring 35,800 [s] to converge is necessary.

7 Conclusion

A comprehensive approach that leverages flow reversals in the optimal design of unconventional gathering networks has been developed. Flow reversals can be an interesting strategy to use surface facilities more efficiently over shale gas production areas. Adding this feature in the network design process permits to reduce pipeline diameters and installation costs. In this work, we have successfully implemented a multi-echelon MIQCP model that includes accurate calculation of pressure drops in any direction for every selected segment. However, quadratic constraints and discrete variables associated with the decision on when to install and how to operate flow reversal equipment lead to large computational burden and solution times.

To address this limitation, we have used an efficient algorithm that iterates between relaxed and feasible solutions (Presser et al., 2023), enabling us to obtain quasi-optimal designs after three iterations, in less than 600 CPU seconds. In addition, we have tested the model and the algorithm in a real-size case study, which results in a shale gas gathering network that takes advantage of the flow reversal, ultimately leading to more than 1.2 MMUSD savings in the total present costs compared to the typical (unidirectional) solution. The iterative algorithm has quickly found good feasible solutions, which prove to be very close to the actual global optimum. As future work, we aim to further improve the efficiency of the model and the algorithm, expanding applications to other types of pipeline networks.

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