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

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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 reversal strategies. The goal is to optimally connect the nodes and install facilities for gathering 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

Pipelines are a highly efficient mean of transportation for liquid and gas products across supply chains. However, the construction of pipeline networks entails significant investment costs, which are only compensated if they are operated at high utilization levels in the long term. The research community has been increasingly focused on the optimal design, planning, and operation of pipeline networks for more than 40 years. 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 recent years, researchers have focused on optimizing the design of gathering networks for unconventional gas production. One of the earliest studies on this topic was carried out by Cafaro and Grossmann (2014). They propose a non-convex mixed integer non-linear programming formulation (MINLP) to optimize the planning of drilling operations over a shale gas area, simultaneously determining the optimal location and size of compressors, pipelines, and gas processing plants. However, recent research has focused on developing more comprehensive models that take into account more details of pipeline operations.

Hong et al. (2020) tackle the problem of optimizing the design of a gathering pipeline system for shale gas production using a piece-wise linear approximation of the pressure drops based on discrete ranges for the flowrates. They solve the problem by means of an ant-colony algorithm that predefines the set of potential connections. Similarly, 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 reduces the risk of operational issues. More recently, Montagna et al. (2022) present a different model that addresses combined shale oil and gas development strategies.

The work presented in this paper can be regarded as an extension of the model developed by Montagna et al. (2022). We make use of a generalized optimization framework for pipeline network design and operation 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 consists of two main parts: topological and fluid dynamics constraints. Firstly, 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 pressures.

Considering pressures as decision variables enables the optimization of flow rates and directions, effectively increasing the utilization of the transportation capacity of the pipeline network. Nevertheless, in the event of a pipeline flow reversal, it becomes imperative to guarantee zero flow when the pressure difference is negative, 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. (Presser et al., 2023)

Reversing the flow of a pipeline segment has the aim of using the same transportation infrastructure to make products flow in the opposite direction. Reversing pipelines can be particularly useful to achieve more economical network designs. Interesting examples of flow reversals are shown in gas primary production, where highly inte-

grated pipeline networks are built and operated to transport gas production 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 prices, yielding mobilization of rigs and fracturing equipment from one region to another. Nevertheless, centralized processing facilities and pipeline networks cannot be relocated. This implies that gas flows may be subject to reversals if the same pipelines are used to send production streams to any of both regions, under alternating 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 accounted for actual capital and operational expenditures associated with flow reversals, never assessing to what extent their complexity can be justified. Converting a pipeline segment into a bidirectional transportation resource requires large capital investment in additional equipment, namely pumps, compressors and valves. Moreover, every time the pipeline flow direction changes from direct to reverse mode, time- and cost-consuming tasks need to be performed. In the work of Cafaro and Grossman (2020), no additional cost has been associated to flow reversals, due to its relatively minor importance when compared to pipeline investment decisions. However, flow reversals costs are particularly relevant in gas pipeline networks.
In the next section we formally define the problem and introduce 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.

2 Problem Definition

The problem addressed in this work involves the design of the network of surface facilities to process shale gas production from multiple wellpads over a long-term planning horizon, while minimizing the expected net present cost of the project under different development strategies. The development plans are based on different gas price scenarios and include information such as the expected productivity profiles over time, the fluid dynamics characteristics of the gases, and the possibility of flow reversals between nodes at different time periods. The global 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.
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 of the pipeline for each segment. And third, identifying the flow direction and transportation rate along each pipeline segment during the time horizon. For planning purposes, the time domain is usually divided into discrete intervals (Saldanha-da-Gama, 2018).

Geographical locations of the 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 pipe diameters to consider for the design, as well as different processing plant capacities for the shale gas. These are decision variables for cost optimization of the pipeline network design, also taking into account constraints from the fluid dynamics of the shale gas transportation and a preselection of the nodes where the plants can be placed.

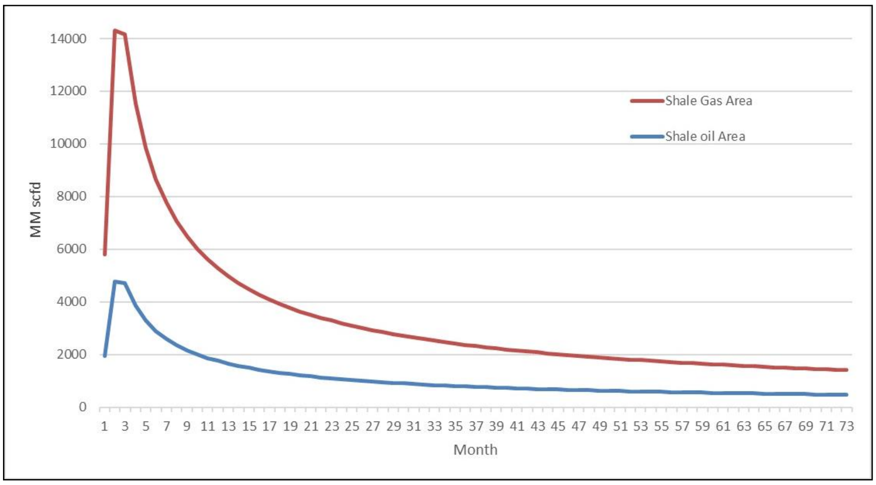

Fig. 1. Characteristic curves of shale gas production in (a) a gas area, (b) an oil area

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.

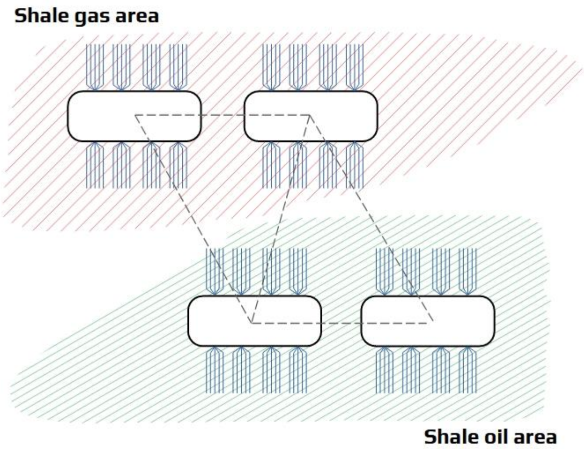

Fig. 2. Wellpads, rows and possible connections

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. As previously mentioned, all possible connections between different nodes allow for reversible flow, meaning that the direction can be changed on a period-by-period fashion.

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 production 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 bimonthly 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 sector row r to sector 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.

$$p_{r,t} + \sum_{r' \in J_{r,r'}} Q_{r',r,t} = P_{r,t} + \sum_{r' \in J_{r,r'}} Q_{r,r',t} \qquad \forall r, t \tag{1}$$

In addition, Eq. (2) implies that all shale gas produced during time interval t must be processed within the same period, excluding the possibility of raw gas storage in this model.

$$\sum_r P_{r,t} = \sum_r p_{r,t} \qquad \forall t \tag{2}$$

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.

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

We also define the set $d \in D$ to account for the pipeline diameters that are allowed. 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 a value of 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.

$$x_{dir_{r,r',t}} \leq \sum_{t' \in TI | t' \leq t} \sum_d \left(x_{r,r',d,t'}\big|_{r<r'} + x_{r',r,d,t'}\big|_{r'<r} \right) \qquad \forall (r, r') \in J_{r,r'}, t \tag{4}$$

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

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

Equations (7) and (8) model the flow reversal feature, which allows changing the flow direction over a pipeline 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 interval. Both the installation and the utilization of this equipment involve specific costs, namely ifr and ofr respectively

$$v_{r,r',t} \geq x_{dir_{r,r',t}} - x_{dir_{r,r',t-1}} - \sum_{t' \in TI|t' \leq t} \sum_d \left(x_{r,r',d,t'}|_{r<r'} + x_{r',r,d,t'}|_{r'<r} \right) \quad (7)$$

$$v_{r,r',t} \leq \sum_{t' \in TI \mid t' \leq t} \left(w_{r,r',t} + w_{r',r,t} \right) \quad \forall (r,r') \in J_{r,r'}, t \quad (8)$$

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. (9) for a given pipeline length and temperature.

$$F = \frac{1.1 \cdot d^{2.667}}{l \cdot s \cdot z \cdot T_1} \cdot \left({P_1}^2 - {P_2}^2 \right)^{0.5} \leftrightarrow F^2 = \varphi^2 \cdot d^{5.334} \cdot \left({P_1}^2 - {P_2}^2 \right) \quad (9)$$

F is the gas flow rate in 10^6 scf/day, 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 $P^{sq}_{r,t}$ specifies the square pressure at the junction of row r during time period t, for unprocessed shale gas transportation, meanwhile $\Delta P^{sq}_{r,r',t}$ refers to the difference of square pressures between two adjacent rows r and r'. In Eq. (10) 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.

$$MaxFlow^2_{r,r',d,t} \leq \varphi^2 \cdot diam_d^{5.334} \cdot \Delta P^{sq}_{r,r',t} \quad \forall (r,r') \in J_{r,r'}, d, t \quad (10)$$

$$\Delta P^{sq}_{r,r',t} \leq \left(P^{sq}_{r,t} - P^{sq}_{r',t} \right) + \Delta sp^{max}_{r,r'} \cdot \left(1 - x_{dir_{r,r',t}} \right) \quad \forall (r,r') \in J_{r,r'}, t \quad (11)$$

$$\Delta P^{sq}_{r,r',t} \leq \Delta sp^{max}_{r,r'} \cdot x_{dir_{r,r',t}} \quad \forall (r,r') \in J_{r,r'}, t \quad (12)$$

$$Q_{r,r',t} \leq \sum_d MaxFlow_{r,r',d,t} \quad \forall (r,r') \in J_{r,r'}, t \quad (13)$$

$$MaxFlow_{r,r',d,t} \leq fmax \cdot \sum_{t' \in TI|t' \leq t} \left(x_{r,r',d,t'} + x_{r',r,d,t'} \right) \quad \forall (r,r') \in J_{r,r'}, d, t \quad (14)$$

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 (11) and (12). $\Delta sp^{max}_{r,r'}$ 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 (13) and (14) limit the maximum flowrate according to the diameter of the pipeline installed between the nodes r and r'.

The model seeks to minimize the net present cost NPC 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. (15), 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.

$$Min\ NPC = \sum_t \frac{1}{(1+i)^{t-1}} \begin{bmatrix} \sum_{r,s}\left(ipf_s \cdot y_{r,s,t}\right) + \sum_{r,r',d}\left(ipl_{d,r,r'} \cdot x_{r,r',d,t}\right) + \\ \sum_{r,r'}\left(ifr \cdot w_{r,r',t}\right) + \sum_{r,r'}\left(ofr \cdot v_{r,r',t}\right) \end{bmatrix} \quad (15)$$

Summarizing, the MIQCP for the optimal design of gas gathering networks aims to minimize the objective function (15), subject to constraints (1) to (8), and (10) to (14), also considering other constraints that are not included due to space limitations (for more details, see Montagna et al., 2022). Note that only one set of constraints in the model, Eq. (10), 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 requirement of monitoring the pressures at the rows connections. The intricate nature of modeling gas flow dynamics contributes to the non-linearity (quadratic form) of this problem, which in turn results in an increase of both the time complexity and computational efficiency 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 distance 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 al-

ready imposed), the proper quadratic constraints are imposed on that connection from that point on. Thus, a relaxed 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 terminated 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 means of validating the optimization model. The example consists of 8 rows of wellpads to be developed in the next 6 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 time 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 (millions of standard cubic feet per day), 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 an NPC 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.

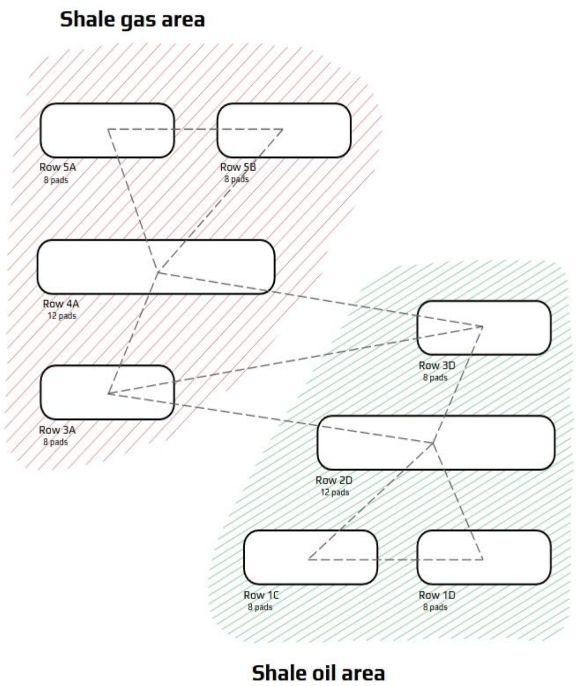

Fig. 3. Case study comprising a shale gas area and a shale oil area with 4 rows each.

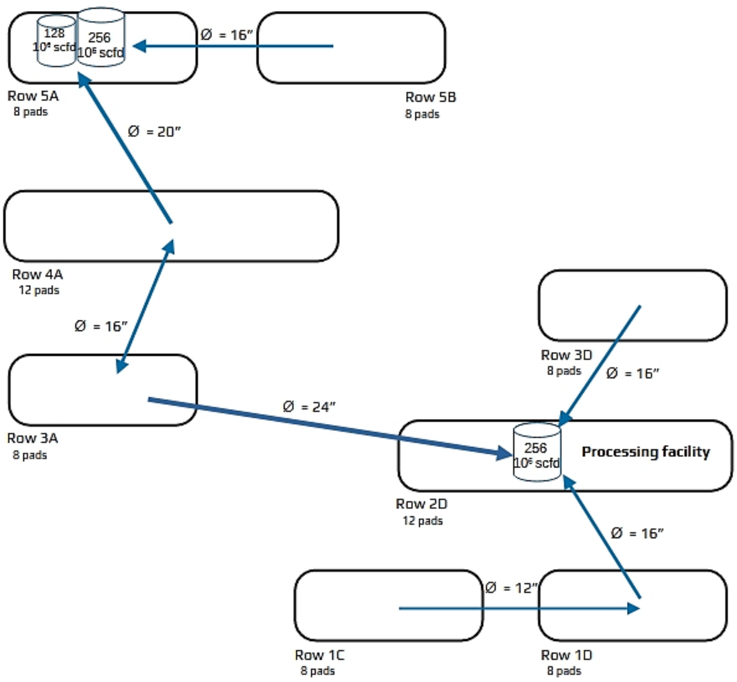

Fig. 4. Optimal solution for case study found by MIQCP model

Table 1. Pipelines investment plan for the optimal solution

Sector Row *r*	Sector Row *r'*	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 NPC for this problem results in 423.2[MMUSD] (shown in Fig.5), saving 1.2[MMUSD] in pipeline costs. Although the total pipeline length and network structure are quite similar, 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.

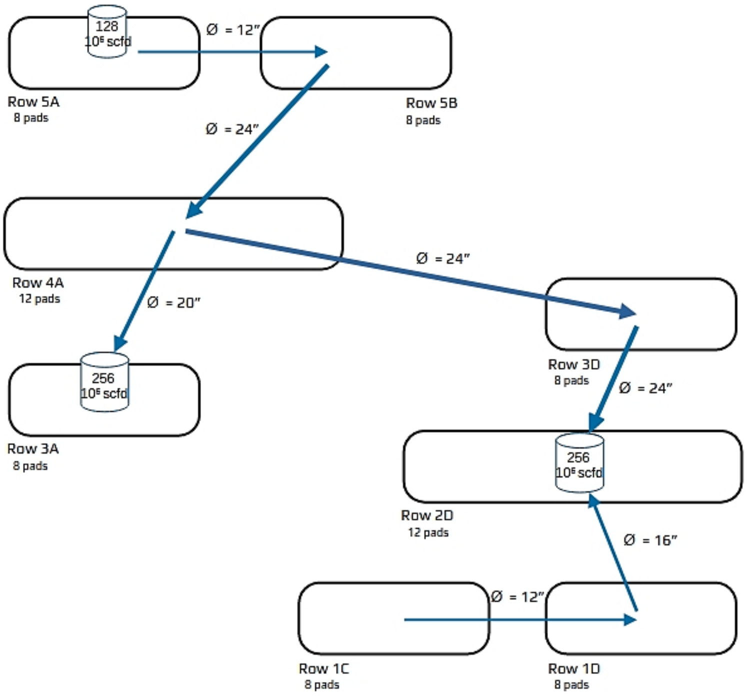

Fig. 5. Optimal solution found without the flow reversal feature

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 processing capacity and the solid line represents the shale gas flow, over the bimesters.

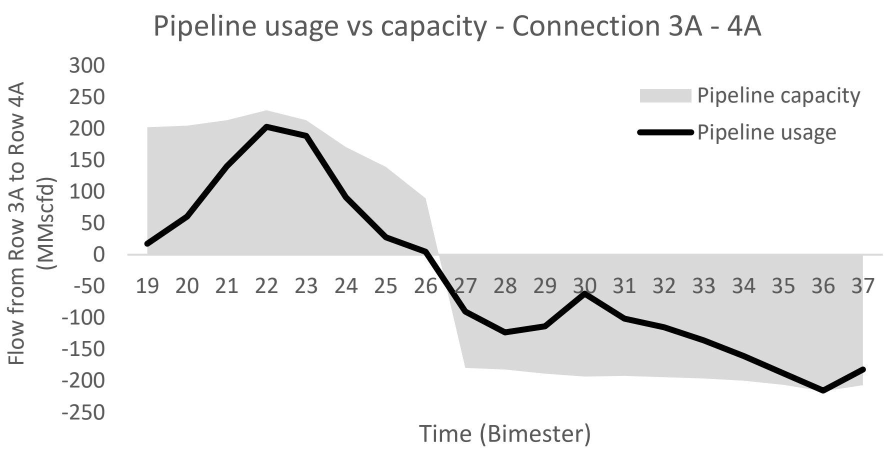

Fig. 6. Pipeline segment 3A-4A utilization in contrast with capacity

Table 3. Model statistics for each iteration of the algorithm

Iteration	Computational time [s]	Accumulated time [s]	Number of equations	Number of variables	Number of binary variables	Relaxed NPC	Feasible NPC
1*	10	10	14505	13924	5844	406.7421	434.517
2*	190	200	16318	14183	5844	408.4577	423.186
3*	370	570	17872	14405	5844	411.3615	422.079
4	1805	2375	18649	14516	5844	414.2108	422.418
5	3785	6160	19685	14664	5844	419.3722	423.916
6	8725	14885	19944	14701	5844	420.0341	423.186
7*	38825	53710	20203	14738	5844	421.7548	421.999

*New best solution found

Table 3 displays the statistical data for every iteration of the algorithm proposed by Presser et al. (2023). It is noteworthy that the number of equations and variables progressively increases with each iteration, as additional pressure drop constraints are included, leading to a longer computational time. 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 solving times. To address this limitation, we have made use of an efficient algorithm that iterates between relaxed and feasible solutions (Presser et al., 2023), enabling us to obtain quasi-optimal designs in less than 10 minutes. 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 net present costs compared to the 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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