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Design optimization of oilfield subsea infrastructures with manifold placement and pipeline layout

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ABSTRACT

This paper presents a practical and effective optimization method to design subsea production networks, which accounts for the number of manifolds and platforms, their location, well assignment to these gathering systems, and pipeline diameter. It brings a fast solution that can be easily implemented as a tool for layout design optimization and simulation-based analysis. The proposed model comprises reservoir dynamics and multiphase flow, relying on multidimensional piecewise linearization to formulate the layout design problem as a MILP. Besides design validation, reservoir simulation serves the purpose of defining boundaries for optimization variables and parameters that characterize pressure decrease, reservoir dynamics and well production over time. Pressure drop in pipelines are modeled by piecewise-linear functions that approximate multiphase flow simulators. The resulting optimization model and approximation methodology were applied to a real oilfield with the aim of assessing their effectiveness.

1. Introduction

In the first stages of an oilfield development plan, after bottom-hole and wellhead locations have been defined, production engineers design the subsea pipeline network to bring hydrocarbons from wells to facilities for processing. The issue is how to structure the subsea pipeline network in a cost effective manner leading to production maximization. In most subsea layout designs, the decisions that have a major impact on the net present value (NPV) include manifold placement, well assignment to manifolds, and pipeline diameters.

The traditional approach to handle this problem consists in selecting a group of experts from several related technical areas to study a few realistic scenarios. Although this approach may yield reasonable layout designs, it cannot guarantee that the mix of options will result in the optimal solution.

On the other hand, mathematical programming methods are widely applied to model and solve investment minimization or net present value maximization problems considering major design restrictions. However, the lack of optimization expertise of technical project teams, allied with the distance of the models to real world situations, discourage engineers from applying optimization techniques.

This paper presents a practical and effective method to design a subsea production network that accounts for the number of manifolds and platforms to be installed, their location, well assignment to these gathering systems, and pipeline diameters. The proposed model comprises reservoir dynamics, multiphase flow, multidimensional piecewise linearization and mixed-integer linear programming (MILP). A MILP formulation was developed for optimal design of the subsea infrastructure, which approximates pressure drops in pipelines with piecewise-linear functions. In a practical setting, often a large number of reservoir simulations are carried out to find a suitable layout. This task can become intractable for a large reservoir for which a single simulation can take several days, depending on the reservoir size and discretization. On the other hand, the proposed approach relies on a limited number of reservoir simulations, making it relatively fast in comparison to the methodology which is often used in practice. The proposed methodology serves as a tool for initial analysis to indicate subsea layouts that can be further detailed, offering key information to guide the decisions in the early stages of development studies.

In many past works, the behavior of the reservoir pressure is modeled as a function of the cumulative production. However, the curve of pressure decay along cumulative production is depen-

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dent on the production infrastructure. This paper also proposes a practical way to overcome this point based on reservoir simulation, performed apart and in advance to define feasible bounds for variables in the MILP formulation.

The approach proposed in this work was applied to the layout design optimization in a real oilfield, for which the results will be discussed below.

1.1. Paper contribution

From the standpoint of production engineering, this work proposes a new and practical approach to the challenging engineering problem of subsea layout design. Differently from other works in the related literature, this paper brings a practical and simple running proposal to optimize subsea layout taking reservoir behavior into account. Possibilities of pipeline routing, diameter definition, manifold placement, and well allocation to gathering systems – manifolds or platforms – are designed by the proposed model in order to maximize NPV, thereby considering the reservoir. This work innovates in subsea layout design by:

- Using the same lift tables of the reservoir simulator to model pressure drop in pipelines with multidimensional piecewise-linear functions.
- Taking pipeline diameter and routing as decision variables, besides manifold placement and well allocation to the gathering systems; this allows the design of the artificial lift method, which could be modeled with different lift tables, one for each pipeline diameter.
- Introducing a simple but practical reservoir model that captures its behavior in different subsea layouts.
- Enabling a fast computational tool to carry out case studies and perform a sensitivity analysis of the manifold and platform capacities.

2. A review of the literature

Subsea layout optimization is often treated as part of field development design optimization. For this reason, most of the papers do not develop layout optimization in details. Some papers address pipeline routing, diameter specification and manifold placing, but these design issues are not handled simultaneously, combined with reservoir pressure updates. Further, the existing literature on layout design optimization is typically targeted at CAPEX minimization or net present value maximization. The latter works usually rely on a simple reservoir model which in most of the cases is too modest to capture the key reservoir dynamics. The former works do not take into account the influence of pipeline pressure drop and reservoir response on well production.

From the literature that treats layout design optimization only as CAPEX minimization, the first notable work is by Devine and Lesso (1972). They proposed a heuristic based on the *p*-median problem to optimize well trajectories and their allocation to fixed platforms, considering coordinates in the reservoir to be reached by drilling. Grimmett and Startzman (1987) also addressed this problem using branch & bound and Lagrangian relaxation, in which the number of platforms is a variable. Hansen et al. (1994) treated the same problem by means of a MILP model solved with a taboo search heuristic.

Fampa (1992) was the first to consider subsea production manifolds in layout optimization. The model considers manifold location and well allocation as a covering problem solved by cutting-plane generation and Balas's algorithm. Given coordinates in the reservoir to be reached by drilling, Ding and Startzman (1996) also tackle this problem as a MILP to optimize trajectories from wells to reservoirs. Their solution consists of a pure branch & bound algorithm which is compared to Lagrangian relaxation applied to the same model. Goldbarg et al. (2002) readdress the work of Fampa (1992) by solving the covering problem with a genetic algorithm.

Cortes (1998) brings about a multi-objective approach that yields a set of layout options to be evaluated by the project team. Platform location is based on a simple version of the facility location problem, like in the Weber problem. Garcia-Diaz et al. (1996) model CAPEX minimization with graphs, whose arcs represent possible links between objectives in the reservoir and whose nodes correspond to candidate locations for platforms. The resulting problem is solved by branch & bound and Lagrangian relaxation.

Nadaletti (2004) points out that the project team can reach better solutions by applying decision tools, in order to define the number and location of subsea manifolds which play a part in CAPEX minimization. Yet, the project team has to decide which models (spanning tree, minimax, or *k*-means) and tools are best suited for layout design. For instance, Xiao et al. (2006) optimize an onshore field layout by solving a capacitated minimum spanning tree problem to define the number and location of manifolds, taking into account pressure drops in pipelines. García et al. (2012) propose a model based on graphs and subgraphs, with the decisions associated to vertices and arcs establishing relations between decisions. Nevertheless, the experience of the project team is taken into consideration to evaluate the solutions produced by the algorithms. Wang et al. (2012, 2014) model subsea manifold placement as a covering problem, in which wells are partitioned into subsets to minimize the total pipeline cost.

It is important to highlight that almost all works that consider well allocation to platforms, in CAPEX minimization, assume that the potential places to install platforms and the wellhead positions are known in advance.

Frair and Devine (1975) made the first attempt to maximize the net present value (NPV) of an asset by considering reservoir dynamics in the subsea layout optimization. They extended the previous work of Devine and Lesso (1972) by introducing a production decline curve for the whole field as the reservoir model. Iyer and Grossmann (1998) considered the optimization of subsea layout design as one of the stages of the proposed algorithm. The problem is modeled as a MILP with a multi-period structure, for which the authors propose an aggregation–disaggregation heuristic that takes advantage of Lagrangian relaxation. Their work comprises the decisions of which wells to drill, the drilling schedule, well allocation to platforms, and the number and capacity of platforms. To render their model tractable, several simplifying assumptions were made: the pressure drop in pipelines is modeled as a linear function of the flow rate; well productivity indexes are constant along time; wells are non-interacting and independent; the reservoir dynamics are represented by a pressure versus cumulative production curve; the fluid pressure is uniform throughout the reservoir; and water is not produced.

Based on Iyer and Grossmann (1998), van den Heever and Grossmann (2000), van den Heever et al. (2000, 2001) considered other design and planning decisions such as the number of platforms, inter-platform connections, platform capacities, investment time, production profiles, and gas compression for exportation. A heuristic based on Lagrange decomposition was applied to the problem thereof. Gupta and Grossmann (2012a) developed a mixed-integer nonlinear programming (MINLP) formulation for multi-reservoir field development and reformulated it as a MILP problem. Their model addresses production planning, well drilling, platform connections to wells and its installations, and expansion planning. In a follow-up work, Gupta and Grossmann (2012b) included fiscal rules and production sharing agreements. Aseeri et al. (2004) introduced oil price uncertainty in the deterministic model of Iyer and Grossmann (1998), and also considered