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An integrated optimization model for the layout design of a subsea production system

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ABSTRACT

A properly arranged subsea production system reduces costs and contributes to production performance due to favorable hydraulic characteristics and flow assurance. Therefore, the layout design of subsea production systems is very important in offshore field development. The design of these systems mainly includes locating the subsea facilities, determining the subsea topology and identifying the pipe route. Each of these three aspects have been studied, for instance, optimization of the pipe network or identification of the optimal single pipe route. However, the combination of these three aspects has not yet been discussed in detail. This paper presents an integrated optimization model for the layout design of a wellhead-manifold-FPSO system, with the aim of obtaining a minimum total pipe length. There are two key details of this model that distinguish it from other models. The first detail is that the seabed topography and obstacles are taken into consideration. The second detail is that all three abovementioned aspects are considered together in the model to determine the optimal number of manifolds, manifold and riser base positions, pipe network topology and pipe routes. The simulated annealing and Dijkstra algorithms are coupled to solve the model by using a newly proposed process. The application of this method is demonstrated by designing the layout of an oil field with 22 wellheads and one FPSO. The results are compared with the situation that neglects the seabed topography, showing a difference in suggested pipe length. In addition, the pipe route effect on both hydraulic and flow assurance is briefly discussed. The model provides a method to link related issues of interest to the layout design, resulting in a practical subsea layout that can be used to more reliably estimate costs, more accurately describe multiphase flow and help in decision-making for flow assurance.

1. Introduction

The development of a subsea field involves a complex design procedure with very high costs. Due to the low oil price, harsh environment, very deep water, high drilling costs and other complicated issues, the challenge of reducing both the CAPEX and OPEX while maintaining an effective development performance is a key consideration. Subsea production systems are widely used for developing deep-water oil fields offshore Brazil, such as the fields in the Campos Basin [1–3], and the pre-salt cluster in the Santos Basin [4–7]. A subsea production system consists of a set of facilities, such as X-trees, manifolds, subsea pumps, and compressors, which are interconnected by flowlines. This flowline network collects and transports reservoir fluid to a processing terminal, for instance, an FPSO platform [6].

Subsea system layout design represents one of the most important aspects regarding cost reduction to consider first [8]. The cost is an issue related to many factors, including the environmental conditions, construction materials, and operation and production requirements, making the problem very complex. Carvalho and Pinto [9] proposed a mixed integer linear programming (MILP) model to determine the connections between the wells and platforms, as well as their installation period, for an offshore oil field. Production variation based on a linearly decreasing reservoir pressure was considered. Gupta and Grossmann [10] adopted a non-linear reservoir pressure drop and developed a mixed integer nonlinear programming (MINLP) model to optimize FPSO installation and connection with target fields. Both studies used the maximum net present value (NPV) as a metric and mainly focused on both the facility cost and production rate. The interconnection of facilities was not discussed in detail in these papers.

The interconnection of facilities determines the pipeline network and affects the system operation efficiency, as well as the cost. Dobersek and Goricanec [11] presented an optimization of a hot water pipe network under hydraulic limitations. El-Mahdy et al. [12] optimized the pipe size used in a natural gas pipe network considering the cost and pressure drop. Sanaye and Mahmoudimehr [13] designed a natural gas transmission network layout considering the pipeline length, pressure

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drop and flow rate. The GA (genetic algorithm) was used to solve the model. Kabirian and Hemmati [14], Üster and Dilaveroˇglu [15], and Mikolajková et al. [16] analyzed the extension of an existing gas pipeline network for the lowest possible operating and capital costs. The connection strategy for the newly added node, the mass flows, compressor duties and changes in the flow directions were optimized. Mikolajková et al. [17] then developed a method of linearizing the MINLP model to accelerate the solving process. Zhang et al. [18] optimized an offshore oil field gathering system considering the flow rate, terrain obstacles, and production techniques. The connection topology, location of the platforms, and major parameters of the pipelines and facilities were determined. One significant similarity of these achievements is that the facilities positions are fixed, and only the connections between the facilities were optimized. Wu et al. [19] and Wang et al. [20] optimized the positions of facilities and pipeline interconnection topology simultaneously for the layout of a chemical industry area, indicating that the positions of the facilities could affect the interconnection strategy, as well as the total cost. Therefore, it could be inferred that for subsea production system layout, the combination of the position determination and interconnection topology optimization might be an efficient way for further cost reduction.

This combination has attracted attention in recent years. Rodrigues et al. [21] developed a 0–1 linear programming model to determine the location of FPSO and manifolds and the interconnection between the facilities. The whole system, from the reservoir to the topside, was taken into consideration. Wang et al. [22] established a model for partition of subsea wells in a layout of cluster manifolds to determine the position of the cluster manifolds and connections with the wellheads. Then, another model was developed to optimize the number and position of pipeline end manifolds (PLEMs), as well as the connections with the cluster manifolds and FPSO [23]. Then, three types of jumper connections were further considered [24]. This method was applied by Hong et al. [25] to design the subsea layout using 4-slot and 6-slot manifolds. The costs of these two scenarios were compared. Rosa et al. [26] developed an MILP optimization method to design subsea production networks, accounting for the number of manifolds and platforms, their location, the well assignment and the pipe diameters.

For these solutions, the connections between facilities were all considered to be straight lines. Practically, an optimal route needs to be designed to fit the environment and operation and production requirements, which are strongly affected by the seabed condition. As a result, the connections might not be simple straight lines and need to be carefully designed.

Single pipe route design has also drawn considerable attention in the past decades. Shamir [27] and Xiao et al. [28] linked route design with the pipe multiphase flow. Meisingset and Olsen [29] set a minimum cost as an object function and optimized the pipeline route under the constraints of seabed topography and pipeline structural properties. Vieira et al. [30] divided the pipe into a set of straight lines and curves and conducted an optimization. Lucena et al. [31] provided a further discussion of this model, considering different constraint handling methods. Then, the model was employed for a route design under a series of constraints such as seabed topography, obstacles, and on-bottom stability with the aim of minimizing the total length [32,33]. Kang and Lee [34] optimized a pipe route and used the Laplacian smoothing algorithm to make the route smoother. Case studies of offshore pipeline route optimization under complicated seabed environments were presented by many researchers [35–38]. Haneberg [39] incorporated the uncertainty of seabed information in a deep-water pipeline route design.

From the literature review, it was found that the combination of location determination of the subsea facilities, subsea layout design, and pipe route optimization has not been worked in detail yet. Combining the above three aspects is logical since they interact with each other, thus affecting the estimated cost. An integral subsea system layout optimization model is proposed in this paper, combining facility positioning and pipe route design, aiming at reducing the total pipeline length and improving production performance. A wellhead-manifold-FPSO system for an offshore oil field is taken as the case study, and the seabed topography is considered, including a set of obstacles. From the model, the position of the manifolds and riser base can be determined, as well as the pipeline network and the corresponding pipe route that allows the shortest pipe length.

The paper is structured as follows. Section 2 and 3 describe the problem and establish the mathematic model, respectively. Section 4 introduces two algorithms, the Dijkstra algorithm and simulated annealing (SA) algorithm, which are used to solve the model. The solving process is then presented. Section 5 presents the case study, in which the model is applied to a deep-water field with a set of wellheads and obstacles, considering the seabed topography. Section 6 provides further discussion on using the model to select a proper combination of manifold sizes. In addition, the traditional method of disregarding the seabed topography is taken into consideration, and the results of the traditional method are compared with those of the proposed optimization model. Section 7 presents the conclusions and suggests future work.

2. Problem description and assumptions

2.1. Problem description

Fig. 1 briefly presents a typical wellhead-manifold-FPSO subsea production system. Hydrocarbons flow out from the set of satellite wellheads and converge at the manifolds, then flow to the riser base, finally arriving at the topside through the riser. To determine the best layout to reduce material costs, the most simple and basic criterion is the shortest pipeline length. In addition, a shorter pipeline length leads to less pressure and temperature loss of the fluid, resulting in less insulation material and power supply. Though there are many factors that influence the total cost, such as flow assurance and structural stability, this paper takes the shortest flowline length as the optimization object, understanding the importance of the integral layout design.

Point (x, y, z) stands for a position in the system, where the x and y coordinates correspond to the horizontal XY plane, and z is the water depth. Different subscripts are assigned to distinguish the positions. The FPSO position is predetermined based on the sea conditions, weather conditions and field location and is denoted by point $F(x_F, y_F, z_F)$. The wellhead positions have commonly been determined based on the reservoir evaluation. The number of wells is n, and the wellhead positions are represented by $W_j(x_{Wj}, y_{Wj}, z_{Wj})$. The subscript j denotes the jth wellhead, where $j = 1, 2, 3, \ldots, n$. Suppose the number of manifolds is m, corresponding to positions $M_i(x_{Mi}, y_{Mi}, z_{Mi})$. The subscript i denotes the ith manifold, where $i = 1, 2, 3, \ldots, m$. One riser base is installed to connect all the manifolds, and is located at the position $B(x_B, y_B, z_B)$. Therefore, the optimal layout with the shortest total flowline length is controlled by the positions of the riser base and manifolds, as indicated in Fig. 1.

2.2. Assumptions

A mathematical model is developed based on the fundamental assumptions described below.

(1) All the pipelines are flexible pipes; therefore, the pipeline route is follows the seabed landscape, and free span is neglected. Consequently, the pipe length is the same as its route length on the seabed surface.

(2) A free hang catenary configuration is adopted for the flexible riser. Practically, a sufficient distance should be left between the riser base and touch down point (TDP) to help absorb the dynamic tension from the riser due to the FPSO motions. This distance is assumed to be constant.