Optimization approach for Arctic field development design using subsea production systems

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Abstract: Russian experience in the design of trunk pipelines and Arctic studies have been used to develop an efficient model and method for Arctic field development design using the subsea production system (SPS). Compared to 2D models used in the past, the new design technique offers an opportunity to make 3D models and can be used for optimization of offshore field development projects. The proposed optimization model is based on the Bellman - Ford algorithm developed for 3D networks. This approach has been used for the first time to capture key features and specific subsea production system design processes. The algorithm and block diagrams developed for the proposed SPS design method is universal. This method can be used to address tasks of a more general nature. Optimization of the particular case between a single start point (well location) and single end point (SPS facility) is implemented as a separate software package, but the scope of applications is not limited by such cases and may be extended even further. It can also be very efficient for Arctic subsea field development.

1. Introduction
The development of offshore oil and gas fields on the continental shelf is one of the priority tasks for the development of the resources of the world’s oceans. This topic is becoming more and more relevant in connection with the growing needs of mankind for raw materials and energy, limited reserves and a significant depletion of continental resources. Thus, the Russian oil and gas industry has ambitious plans to develop offshore hydrocarbon fields located in the frontier Arctic regions and other areas with similar conditions. The total of 78 licenses have been registered for development of the Russian shelf sector. Most of them are located in the Arctic region. Development of these licenses will require advanced scientific knowledge and high-tech technology for production of unconventional resources.

2. The complexity of the development of Arctic hydrocarbon deposits
The Russian Arctic has the most challenging environment and extreme weather conditions including presence of ice, hummocks, icebergs, low temperatures, permafrost, strong winds, waves, currents, and a short navigation season. Another important consideration is that the Arctic is a remote area with no infrastructure.

This requires extended use of unmanned facilities, application of special equipment and work procedures in full compliance with the relevant standards and regulations. Additionally, all materials used in the Arctic region shall be designed for low temperature applications [1]. The subsea production technology can be an efficient solution for offshore field development applications in the Arctic region.
3. SPS. Promising technology and solutions, but a challenge
Subsea production systems are widely used in offshore development projects worldwide. Since 1961, quite a few offshore fields have been developed and brought on stream using subsea production systems or their components (West Cameron field in the Gulf of Mexico). Currently, over 130 offshore fields [2] use technological processes designed for subsea hydrocarbon production.

Russia has a very limited experience in the use of subsea production systems. There is only one SPS system installed and operated in Kirinskoye gas condensate field (Russian Federation), however the demand for subsea system components in Russia over the period until 2035 is estimated at 400 components.

The subsea production technology can be used to address multiple problems encountered during field development activities in the Arctic region. Nevertheless, the cost and complexity of manufacturing and installation of subsea production systems is quite high, and the average facility would cost hundreds of millions of USD. For example, in 2012 the total worldwide CAPEX and OPEX for subsea production was over $250 billion [3]. Application of more efficient design methods is a potential option for cost reduction during implementation of subsea production systems.

4. An optimization approach is needed to reduce costs and solve design problems
Analysis shows that there is a number of models used for optimization of line facilities primarily for onshore field development applications and construction of different infrastructure facilities.

Thus, attempts were made to optimize the routes of highways based on the algorithm of a probabilistic roadmap taking into account the relief of the Earth's surface and obstacles [11]. That is, we consider the search for the optimal road route with the minimum value of the objective function of the construction cost from the starting point to the final point on a given surface, bypassing obstacles.

The National University of Oil and Gas "Gubkin University" conducted a global study to select the best trunk pipeline route [4-9]. The study used export/trunk pipeline route optimization methods based on Bellman's optimality principle (dynamic programming principle) and Lee's algorithm. 2D network models were used for simulations.

Figure 1 shows network geometries used for calculations: rectangular with diagonals, and arbitrary.

Another study conducted by Kornienko O.A. reviews different methods to select the most efficient installation sites and types of subsea production systems, facility capacity estimation methods for offshore infrastructure facilities, and selection of optimized layouts for offshore field development applications. Nevertheless, all proposed models are deemed to be project-specific and localized solutions for subsea production optimization [10].

Further analysis showed that SPS optimization using the methods developed for main pipelines will be limited and it was decided to consider the path of the well fluid as a whole - from the bottom of the well and beyond. However, the existing optimization models based on 2D networks turned out to be inapplicable and the possibility of implementing the optimization approach on 3D networks with diagonals was considered.
5. Optimization approach for Arctic field development design

The current study is the first ever attempt to use an optimization method based on selection of the shortest optimal path using 3D models with diagonals.

Note that the proposed approach is universal and can be used for selection of the best layout at any location and in any environment, but its application will be most efficient in the Arctic region. Optimization for this case is a very challenging task (SPS systems include seafloor facilities) since SPS system layout greatly depends on field development pattern (bottomhole locations) and produced fluid intake facility location (platform / FPSO / onshore).

SPS systems with horizontal line facilities (pipelines for various purposes, umbilicals, etc.) and vertical facilities (wells) are considered jointly in this article. Therefore, this method suggests projecting SPS systems and wells to a spatial (3D) network model (see Figure 2).

Figure 2. Example of the 3D model with diagonals for selection of the most efficient SPS design for future field development (diagonals are shown in one cell only for illustrative purposes).

It is suggested to select the most efficient SPS system layout using a 3D model built on a regular grid with parallelepiped diagonals and specific number of nodes on different axis:

- \( M \) - nodes along the x-axis
- \( N \) - nodes along the y-axis
- \( L \) - nodes along the z-axis

The starting point \( H \) corresponds to the center of the deposit and has coordinates \( x_H, y_H, z_H \). Location of this point is fixed and defined by geologists. The start point overlaps with the nearest host. The top plane of the 3D model is deemed to correspond to the bottom surface, including the coastline (if necessary), and the end point shall be located on this plane and correspond to one of the nodes.

\( K \) is the end point with coordinates \( x_K, y_K, z_K \). The segments between adjacent nodes define the value of the selected optimality criteria (hereinafter called \( C \) costs since it is the most frequently used criteria).

The most important optimization criteria may include:

- Expenses over the project life
- Time index
- Risks including safety
- Other criteria
Therefore, value of the criteria shall be determined for each segment. This includes a value for capital investments:

- Allocated costs (e.g. cost per 1 km of well / pipeline / umbilical)
- Focused costs (e.g. subsea well completions, manifold, subsea storage, etc.)

For the purposes of SPS optimization for Arctic projects or similar areas, cost estimates shall incorporate all driving factors which might impact the cost. Thus, the main task is to select the shortest cost path between the start (s) and end points in the proposed 3D model. That means that we need to select \( W_{\text{opt}} \) points from the set of points in the \( W_{3D} \) model which meet the following criteria:

\[
C_{W_{\text{opt}}} = \min \text{ from a variety } C_{W_i},
\]

Where,

\[
\sum_{i}^{x} C_{W_i}
\]

\( i \) – Number of nodes sitting on the optimal path

The workflow requires generation of multiple paths in the network for consequent analysis using the Bellman - Ford algorithm where each path has specific features such as node coordinates for different components, cost of reaching a final node along the selected path, and other parameters.

The basic principles of this approach are shown below using an example case study for SPS optimization. In this example, the search is carried out from the start point corresponding to the bottomhole location to the end point, which can be a horizontal projection of the platform/FPSO or landfall point. The start and end points are aligned with the nodes of the 3D network. Selection of the best field development option using SPS systems is performed on the basis of the selected criteria and potential limitations.

Note that the optimality criteria are not a linear (additive) parameter, and therefore, conventional optimization methods are not applicable in this case. For example, a surface well has a dramatic increase of optimality criteria due to a subsea well completion. With this increase, characteristics of the test path also change. It extends along a two-dimensional network with other values of the criteria. A fragment of the block-diagram for the case "One start point - one end point" are shown in Figure 3, and Figure 4 shows a detailed fragment of a part of the block diagram.

Basic assumptions include:

- For the purposes of this calculation, the cost of network sections is proportional to the measured length of the sections.
- The cost criteria for segments not belonging to the bottom surface \( C_p \) is equal to 1 million of conventional units. It actually corresponds to construction of 1 well length.
- For the segments belonging to the bottom \( C_b \), the unit of length is 0.5 million conventional units. Physically, it would mean the cost of laying the umbilical and pipeline.
- A cost increase is observed when the bottom is reached. It corresponds to \( C_c \). It occurs due to the cost of the equipment at that point (template, X-mas tree, protective cover, etc.).

\[
C_p = f(C_o, C_s, C_{con}, C_a) \quad (2)
\]

\[
C_b = f(C_o, C_s, C_{con}, C_a) \quad (3)
\]

\[
C_c = f(C_o, C_s, C_{con}, C_a) \quad (4)
\]

Where \( C_p \) - cost of facilities, \( C_s \) - cost of delivery, \( C_{con} \) - cost of installation and \( C_a \) - other costs

Meanwhile, the cost of each parameter depends on the location, hydrometeorological conditions, water depth and other characteristics, which will be discussed in more detail at a later stage. The search is carried out using two lists: "List 1" and "List 2". Theoretically, we need to build the paths in all directions allowed by the network, however, for the sake of time saving, calculations will be performed for the paths with physical meaning only.
Then the path with the minimum cost will be selected (in case of multiple paths only one is selected). The process will continue using the same workflow: every selection from the remaining paths in List 2 shall end up with selection of a path with minimum cost. At some point the selected trial path will reach the bottom. When it happens, the constant value $C_c$ is added to the cost of the original trial path, and adjacent points located on the bottom plane will be integrated. During the next phase, the paths which run only through the bottom will be generated. Their cost will be equal to $F(C_b)$. The remaining paths continue to be generated using the same procedure.

The process will continue until an end point is added to List 1. After that, the selected path will be restored. To achieve this end, the Step Number column from the table in List 1 and 2 will be used. List 2 is used to define an adjacent point in the same line of List 1. This process will continue until the start point is reached.

This particular case example (one start point - one end point case) describes the particular problem that shall be solved. In addition, this case shows a typical workflow to solve the general case with several wells located on a template with consequent production and transfer of the product via subsea processing facilities to a fixed-floating facility or directly to an onshore installation, and it also can be used for the case with product transfer from reservoirs to treatment facilities.

**Figure 3.** - Block diagram of the selection process during optimization of the field development pattern using a subsea production system, particular case.
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Figure 4 - Block diagram: field development pattern optimization using SPS systems, particular case (continuation).
6. Conclusions
From this study, the following conclusions are drawn:

- The analysis of the possibility of optimizing subsea production systems showed that it is incorrect to consider them only as linearly extended objects. Optimization in this case will be incomplete.
- It is necessary to consider the subsea production system and wells together, however, it is impossible to use the existing optimization methods developed for 2D networks.
- In this regard, an optimization approach based on the use of a 3D model was proposed.
- The developed algorithm and block diagram for the simplest, but real case - one start point-one end point - make it possible to make a statement about the possibility of optimization when taking into account SPS and wells together, using the Bellman - Ford optimality principle and the Lee algorithm.
- The analysis also showed that the proposed method will be most effective for Arctic conditions.

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