Iranian Journal of Oil & Gas Science and Technology, Vol. 3 (2014), No. 3, pp. 26-38
http://ijogst.put.ac.ir

Optimization of the Cost Function in the Drilling of Oil Well Network by Balas Algorithm

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Received: January 02, 2014*; revised:* May 20, 2014*; accepted:* June 15, 2014

Abstract

The most costly operation in the oil exploration is the well network drilling. One of the most effective ways to reduce the cost of drilling networks is decreasing the number of the required wells by selecting the optimum situation of the rig placement. In this paper, Balas algorithm is used as a model for optimizing the cost function in oil well network, where the vertical and directional drilling is performed. The model can determine optimal well placement as well as optimal paths to develop the field. The proposed model is implemented in an Iran southern gas field with five drilling rigs used to drill 44 wells from 14 positions on the surface. The results show a 17.4% reduction compared to the proposed cost.

Keywords: Oil Wells Network, Optimizing, Directional Drilling, Balas Algorithm, Cost Function

1. Introduction

The oil exploration systems consist of a complex network of oil and gas wells, some of which sometimes exceed several hundreds. In the well network, the appropriate path determination of vertical and horizontal wells is very complicated and depends upon many factors. These factors include the conditions of geology, reservoir and fluid properties, the required equipment, economic criteria, etc. (Bangerth et al., 2004). Drilling management is necessary for the efficient use of rigs and drilling operations in order to achieve minimum cost and time. Therefore, the operation research techniques can be employed appropriately. Although the problem of optimal well placement in a reservoir has not completely resolved yet, many methods for optimizing the parameters do exist. These methods include genetic algorithms, polytrophic algorithm, Kriging algorithm, neural networks, numerical simulation, or a combination of them known as hybrid techniques (Guyaguler and Horne, 2001). The goal of optimization is to find the best arrangement of wells with the specific target function, often the net present value, which is to be maximized. The problem of the determination of the optimum position of several wells, producing from a two-dimensional closed-boundary reservoir, to maximize the cumulative production has been investigated (Camacho et al., 1996). In another work, the geostatistical approach, which is based on the simulated annealing method and is particularly well suited for optimizing highly combinational problems such as the static problem of selecting well locations, was carried out. Siemek and Stopa (2006) investigated the optimal location of wells in a gas reservoir by using the simplex method. The objective function was the determination of the optimum wells for production operations with a specific rate from Wierzchowice gas reservoir. Often decision-making about the location of wells is an optimization

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problem that helps to generate a greater production, but the drilling costs are not considered alone. Therefore, this paper represents a method based on Balas algorithm in order to minimize the cost function in the drilling of oil well networks.

The papers mentioned herein are mainly used for the optimization of the well or rig placement in the production stage; but, the current paper offers a new approach in the drilling networks, which considers solely drilling costs. In the exploratory phase of the project, regardless of income producing purposes, wells are offered at a minimal cost. The model is suitable in the exploratory stage, but not appropriate in the case of very little income. The research on this subject is entitled “Rig Placement Problem”. The paper with a similar subject, which is presented by Carvalho and Pinto (2005), is entitled “An Efficient MILP-based Solution Technique for the Planning of Offshore Oilfield Platforms.” In this paper, the objective function that must be maximized is the net present value (NPV). This function has two components, namely the revenues from oil and gas production, and the cost of installing rig, path drilling, and finishing operations. The model controls discrete and continuous parameters in different periods. In the proposed model, capital limits are also included; therefore, the model can solve more complex problems. This method was used to solve a problem with 500 wells and 16 rigs in a 10-year timeframe (Carvalho and Pinto, 2005). Other researchers such as Iyer et al. **(**1998), Van Den Heever and Grossmann (2000) have studied the optimizing models for oil exploration by offshore platforms. Another work focusing on rig placement also presented a model for solving the problem (Bather and Benkherouf, 1991). The present paper continues to work on “Rig Placement Problem” by using other methods.

Today, the available technology allows most fields use directional drilling. The directional drilling cost depends on the path length and the deflection angle from the platform to the target point. The platform requires the investment costs, normally from a quarter to $10 million. For a certain land, the rig cost has a very close relationship with the water depth and the number of wells to be drilled by the rig. Thus, for a large number of wells (25 to 300 wells), an optimization problem will happen with the aim of finding the number, size, and locations of drilling rigs and the wells assigned for each platform. The model object minimizes the drilling costs and rig leases. This problem is known as “The Rig Placement Problem” (Bather and Benkherouf, 1991).

The determination of rig placement is structurally equivalent to the known problem “Determination of the warehouse location”. The platforms are the same as the stores and the target points in the reservoir correspond to goods that are in a storage place. The cost of drilling platforms to target points in reservoirs is the same as the cost of goods transportation between warehouses and the factory. Of course, the drilling cost will depend on the rig position. The platform cost as a whole depends on the water depth and seabed conditions (Balinski, 1961).

For the complexity of the real world, it is impossible to provide an exact model of oilfield development, because it adds a lot of factors such as the random nature of the drilling costs, uncertainty about the exact nature of the field, current economic conditions, environmental standards, and so on. Therefore, the optimal answer of the model does not mean that the analyst provides the optimal answer to using it in reality. The most important feature of the model should provide a better understanding of how the total cost of oilfield development is dependent on various parameters. Certainly, these considerations should be taken into account, when the method or methods provide a solution to the model.

2. Modeling

The selection of *N* locations for installing drilling rig in order to drill *M* target points in the reservoir is termed a multiple-choice problem (Hillier and Lieberman, 2007). The vertical and directional drilling of oil wells used for several targets in an oilfield is a multiple-choice problem. It assumes that *N* locations can be drilled to *M* target points in a field. Their paths drilled with vertical and directional drilling are shows in Figure 1.

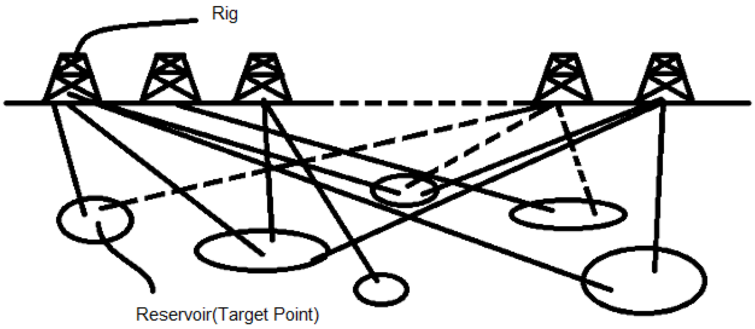

Figure 1
A schematic of rig locations (*N*) and target points (*M*).

In this model, the optimal locations for drilling in situations of the lowest overall cost are selected. This model can be formulated as (Ahmadi, 2010):

Setting x_{ij} as drilling from position *i* to *j*, then one may suppose:

$$x_{ij}\begin{cases}1 & if\ drilled\ from\ i\ to\ j\\ 0 & not\ drilled\ from\ i\ to\ j\end{cases} \tag{1}$$

Assuming that every position such as *i* has been drilled at least one time, then the rig will be in position *i*. This can be shown as:

$$y_i=\begin{cases}1 & if\quad \sum_{j=1}^{M}x_{ij}\geq 1\\ 0 & if\quad \sum_{j=1}^{M}x_{ij}=1\end{cases} \tag{2}$$

In the definition of inequalities, the relations between the parameters, limitations, and other experiences required in the project or represented by the employer must be considered. These situations include the maximum number of rigs, the maximum displacement for each rig, and the minimum and maximum of the target points for each rig. Generally, there are constraints that are often as follows:

1- Each target point is drilled only by one rig, i.e.:

$$\sum_{i=1}^{N}x_{ij}=1 \qquad (j=1, 2, 3\ldots M) \tag{3}$$

2- Uniformity in the use of rigs: The heavy use of a rig may cause other rigs not to work properly, and therefore may considerably increase costs. The maximum and minimum number of rigs can be determined based on the number of target points (*M*), the number of available rigs, and the minimum time of the rig rental. Thus, the limiting equations for any rig can be given by:

$$B\times y_i\leq\sum_{j=1}^{M}x_{ij} \qquad (i=1, 2, 3\ldots N) \tag{4}$$

$$\sum_{j=1}^{M} x_{ij} \leq K \qquad (i=1, 2, 3\ldots N) \tag{5}$$

The model variables and parameters have been summarized in the nomenclature.

The objective function is equal to the drilling costs, which are equal to the operating costs of the drilling rig added to path drilling costs and the cost of the drilling rig operation. Therefore, the cost of the objective function of the drilling network is expressed by:

$$C_T=\sum_{i=1}^{N}\sum_{j=1}^{M} C_{P_{ij}}\, x_{ij} + \sum_{i=1}^{N} S_i\, y_i \tag{6}$$

To determine the exact objective function, the type of operations and how to use the rig should be noted.

3. Methodology

In this section, the effects of the drilling path and rig on the objective function of the model are presented.

3.1. The path effect

If the path is drilled by a vertical drilling, it is only one path from *i* to *j*; but, if directional drilling is preformed, depending on paths shown in Figure 2, there will be four alternatives, namely A, B, C, and D.

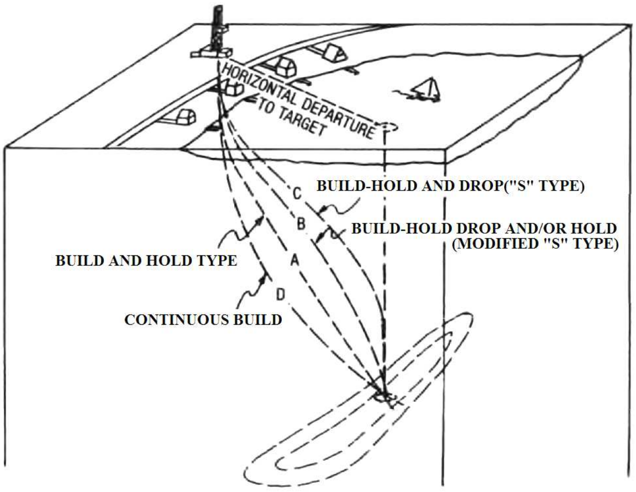

Figure 2
Various forms of a directional well (Bourgoyne Jr. et al., 1991).

Thus, the path cost based on the vertical and directional parts according to Equation 7 will be obtained by:

$$C_{P_{ij}} = D_{ij} + V_{ij} \tag{7}$$

For various directional paths, there are 4 forms of drilling costs per meter (k'_{1ij}, k'_{2ij}, k'_{4ij}, and k'_{3ij}). Drilling costs increase by increasing depth (Adam, 1991); however, for simplicity, average drilling costs are considered. The cost can be determined by comparing the drilling costs of the similar depths and formations. The total cost of the drilling network according to Equation 8 can read (Jafari, 2013):

$$C_p = \sum_{i=1}^{N} \sum_{j=1}^{M} a_{ij}\, C_{P_{ij}} x_{ij} = \sum_{i=1}^{N} \sum_{j=1}^{M} a_{ij} \times \left(K_{ij} \times LV_{ij} + K'_{ij} \times LD_{ij}\right) \times x_{ij} \tag{8}$$

There are N numbers of locations that allow the installation of a rig. These locations can be determined by practical considerations. M is the number of points determined by the exploration team, based on previous data, and the needs. For some points, the upper formations are identified as essential. In this case, the proposed model considers the vertical drilling as a necessary limitation. In operating situations where the drilling of some paths is impossible, the drilling possibility coefficient (a_{ij}) is defined by Equation 9:

$$a_{ij} = \begin{cases} 1 & drilling\ from\ i\ to\ j\ possible \\ 0 & drilling\ from\ i\ to\ j\ impossible \end{cases} \tag{9}$$

It is necessary to determine the drilling possibility of each path. According to different directional drilling techniques, one can drill different paths from each *i* to *j*. Some of these paths are not drillable, because the geological and operational conditions are not suitable. In this case, to simplify the model, from each *i* to *j* only one path is considered. According to Equation 10, the effects of technical conditions can be identified as follows:

$$a_{ij} = rf_{ij} \times rd_{ij} \times \ldots \tag{10}$$

where, rf_{ij}, rd_{ij}, … are binary parameters defined according to each condition. If the condition is not right, the related parameter is 0, otherwise it is 1. If one of the conditions is equal to zero and the other conditions are satisfied, the drilling possibility coefficient (a_{ij}) equals zero, and therefore the drilling of the path is impossible. Among the conditions which are effective in defining and determining the parameters rf_{ij}, rd_{ij},… one may refer to:

a) The horizontal distance of the rig to the target point (rd_{ij}): in order to determine the distance limitation, the rig characterizations must be studied.

b) Formation condition (rf_{ij}): this condition can cause some problems during and after the drilling, including hardness of rock, loose or fractured strata, water-bearing layer, the layers of salt and shale, and so on. To determine the conditions (rf_{ij}, rd_{ij},…), the status of implementation in geology terms and the ability of machines are necessary. After determining the possibility coefficient (a_{ij}) for all the paths from Equation 10, the model selects *M* paths from possible paths so that the cost objective function is minimized.

3.2. The rig effect

In this model, for simplicity, the rig number is unchanged during the project. A location is selected in such a way that at least one rig has access to each target point in the reservoir. In general, the number of possible locations for the installation of rigs (*N*) is greater than the number of rigs; therefore, after drilling some wells during the project, the rig may be moved to another location to drill additional wells. The rig costs according to Equation 11 are given by:

$$C_R = \sum_{n=1}^{N} t_n \times c_n \tag{11}$$

where:

$$C_n = C_{1n} + C_{2n} \tag{12}$$

The rig daily costs include the rig daily rental and daily operating costs. Thus, using Equations 8 and

11, the total cost or objective function, according to Equation 13, becomes:

$$C_T = C_R + C_P = \sum_{n=1}^{N} t_n \times (C_{1n} + C_{2n}) \times y_i + \sum_{i=1}^{N} \sum_{j=1}^{M} a_{ij} \times \left(K_{ij} \times LV_{ij} + K'_{ij} \times LD_{ij}\right) \times x_{ij} \qquad (13)$$

According to the standard form of Balas algorithm, the objective function is minimized (Taha, 2007) and is subsequently used to obtain the lowest drilling cost.

4. The numerical implementation

The model is herein used to determine the minimum drilling cost in a drilling network of an Iran southern gas field. For the model calculations, the drilling network project, as shown in Figure 3, is divided into 49 blocks with a size of 1×1 km^2. The coordinates of the target points in the reservoir and the possible locations of rig installation are shown by hollow points (right) and full points (left) respectively. The target points are numbered from the top left corner to the bottom right corner; such a numbering method eliminates any crowding.

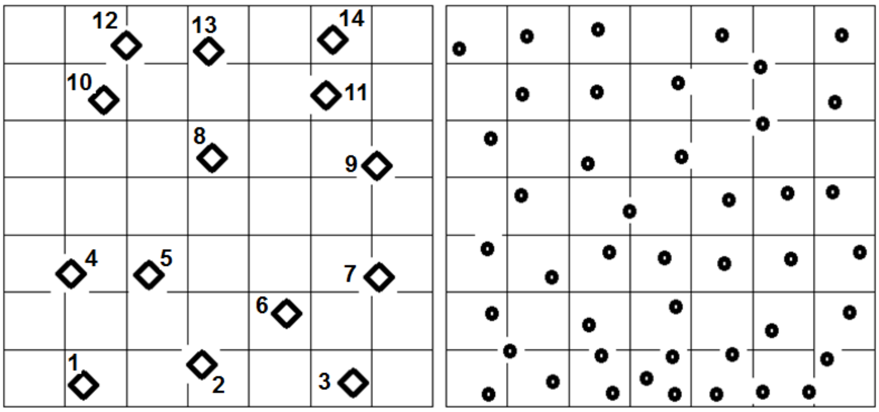

Figure 3
The rigs possible locations on the surface (left) and target points in the reservoir (right).

In this field, 5 rigs are used to drill 44 paths out of 1939 possible paths with the minimum total cost. The drilling costs depend on factors such as the location of rig installation, rig size, the availability to drilling location, environmental and geological conditions, the drilling path, and the total length which has to be drilled. Environmental conditions such as water depth, reservoir depth, and the geological conditions are not changing. Obviously, increasing the depth of the water needs larger rig sizes (Molvar, 2003). The drilling paths are selected according to geological factors, reservoir parameters, subsurface conditions, and drilling instruments. The selection of a drilling path from a rig (*i*) to a target point (*j*) and the drilling cost of the paths are not different from each other and do not affect the total drilling cost (Bourgoyne Jr. et al., 1991). Finally, the most important factor, which influences the total drilling cost of a well, is the total drilled path length. Nevertheless, this relation is not linear, because the total drilling cost of a well depends on the time spent on drilling. Deeper drilling increases the necessary time of drilling and therefore the drilling costs are several times more than the upper section of the well (America Petroleum Institute, 2010).

Each rig, which is located in 14 possible locations, can be accessed by 44 target points; but, there are some limitations to access the points. Firstly, each rig can horizontally deviate to a maximum of 2700 m. Secondly, in order to avoid idle rigs, the target points are divided between rigs. In this example, the number of paths for each rig is 8-12. According to the contract, the contractor must use 5 jackup rigs.

The rig cost is not determined separately and is considered 10% of the total cost, including operating costs and the capital expenditure. This is considered to amount to US$ 175 million. The objective function by Equation 13 is thus obtained by:

$$C_T = 175000000 + \sum_{i=1}^{14} \sum_{j=1}^{44} a_{ij} \times \left(K_{ij} \times LV_{ij} + K'_{ij} \times LD_{ij}\right) \times x_{ij} \tag{14}$$

If the horizontal length of the path is over 2,700 meters, then x_{ij} equals to zero; namely:

$$2700 < \sqrt{\left(x_j - x_i\right)^2 + \left(y_j - y_i\right)^2} \rightarrow x_{ij} = 0 \tag{15}$$

Thus the maximum and minimum numbers of paths drilled by each offshore drilling rig are given by:

$$8 \times y_i \leq \sum_{j=1}^{44} x_{ij} \qquad (i = 1, 2, \ldots, 14) \tag{16}$$

$$\sum_{j=1}^{44} x_{ij} \leq 12 \qquad (i = 1, 2, \ldots, 14) \tag{17}$$

Each target point (*j*) must be drilled only by one rig, namely:

$$\sum_{i=1}^{14} x_{ij} = 1 \qquad (j = 1, 2, \ldots, 44) \tag{18}$$

The term LV_{ij} depends on the final depth of drilling, methods of deviation, and well completion equipment. Any target depth which is greater than the deviation starting point is also larger in depths. LV_{ij} and LD_{ij}, as the available data, are given in Tables 1 and 2. One meter drilling costs by jackup rigs are different at different depths of the well. Herein, the average drilling cost is considered the same for the vertical part. In the directional part, the average of the drilling cost per meter is considered based on the range of the different depths, as listed in Table 3, K_{ij}=US$ 89.45.

Table 1

The LV_{ij} values of drilling paths.

	***i*=1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
***j*=1**	1798	1865	1476	1932	1834	1820	2371	2938	2345	5000	3862	5148	4929	3923
2	1703	1746	1534	1912	1927	1832	2633	3128	2484	5118	3928	5206	4987	3978
3	1723	1689	1621	1903	2184	1783	2817	3283	2678	5090	4006	5207	4988	4012
4	1956	1934	1595	1977	2467	1738	2938	3526	2681	4235	4458	4973	4754	5022
5	1850	1763	1599	2231	2746	1808	3178	3673	2717	4132	4675	4351	4138	5093
6	1652	1452	1632	2763	2849	1837	3718	3827	2817	4234	5169	4873	4728	5134
7	1962	1883	1763	2976	2938	1892	2928	4234	2981	5198	3928	5009	4719	4827
8	2006	1920	1945	3007	3011	1987	3210	4389	3072	5134	4312	4995	4776	4982
9	1903	1854	1986	3095	3199	2109	3481	4827	3267	4928	4975	4928	4709	4994
10	1900	1832	2167	3157	3349	2485	3517	4878	4938	3965	5127	4893	4673	4903
11	1996	1892	2458	3876	3235	2745	3711	4976	4827	3869	4982	4219	4030	4969
12	1793	1762	2645	3249	3598	2937	3827	4278	3281	5003	3755	4573	4354	3981
13	2011	1934	2986	3976	3827	3181	3928	4356	3827	4879	3821	4519	4301	3827
14	2037	2001	3089	3284	3928	3124	3982	5197	4129	4659	4658	4441	4222	4023
15	2361	2113	3167	4357	4213	3356	4171	4182	3928	4154	4345	4129	3910	3792
16	2741	2245	3234	3956	4254	3456	4299	4283	4281	4100	4376	4056	3838	3817

	***i*=1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
17	2501	2061	3562	3786	3583	3748	4352	4482	4928	3987	4569	4028	3809	4281
18	2239	2119	3311	3643	3352	3878	4448	4394	5203	3867	4328	3993	3734	4361
19	2038	1994	3145	3563	3281	3945	4628	4192	5197	3678	4876	3928	3709	4259
20	2951	2654	3247	5201	4324	3648	4502	3918	3483	3670	4140	3726	3507	3674
21	2903	2849	3769	5109	5018	3892	4682	3928	3249	3582	3976	3643	3424	3517
22	3501	3421	4110	5029	5145	3982	4893	3827	3198	3643	4003	3734	3515	3672
23	3556	3458	3933	4365	5016	4191	4927	4181	3318	3522	4201	3689	3470	3618
24	3124	3276	3970	4129	4963	4982	5010	4229	3617	3511	4315	3576	3354	3678
25	3567	3219	4121	3785	4879	4839	5021	4018	4783	3456	4398	3565	3234	3783
26	3762	3008	4021	3001	4238	4783	5189	3928	4837	3214	4406	3461	2905	3754
27	4132	4120	4002	5012	4987	3478	3928	3627	3217	3107	3781	3124	2654	3012
28	4566	4123	3991	4996	5028	3855	4289	3726	3315	2918	3617	2981	2734	2983
29	4876	4460	4532	4977	4835	4789	4978	3638	3837	2899	3879	3087	2573	3041
30	4576	4198	4821	4567	4328	5082	5111	3561	3519	2918	3899	2918	2568	2936
31	4299	4367	4751	4734	4128	4647	5203	3170	4017	2819	3902	2914	2560	3132
32	4002	3989	3987	5005	4521	3478	4110	3167	3527	2709	3628	2905	2436	2871
33	5098	4870	4129	4989	4874	3874	4282	3091	3519	2673	3673	2781	2328	2864
34	5149	4710	4256	4876	4568	4277	4428	2981	3831	2617	3627	2721	2256	2892
35	4279	5010	5101	4358	3984	4937	4983	2817	3729	2567	3599	2773	2238	2981
36	4329	4989	5198	4298	3674	5002	5008	2763	3928	2456	3528	2681	2225	3012
37	5112	4671	4100	4238	4184	3789	4281	2618	3292	2487	3256	2781	2199	2781
38	4990	4298	4428	4261	4236	3799	4381	2517	3319	2341	3387	2673	2012	2526
39	4876	4880	4672	4218	4135	4013	4583	2736	3428	2234	3281	2601	1928	2498
40	4557	5200	4956	4100	4382	4283	4420	2744	3279	2201	3198	2583	1827	2429
41	4320	4672	5006	3986	3997	4585	4573	2637	3749	2108	3289	2573	1863	2398
42	4120	4176	5099	3488	3742	4858	4204	2467	3771	2008	3516	2315	1798	2593
43	3781	3245	5120	3141	3484	4897	4602	2178	3536	1935	3462	2344	1791	2572
44	3456	3164	5193	2953	3844	4928	4802	2168	3871	1923	3482	2205	1627	2581

Table 2
The LD_{ij} values of drilling paths.

	***i*=1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
***j* =1**	2992	2335	2724	2268	2266	2780	2829	2262	2262	2855	1338	52	271	1277
2	2897	2454	2666	2288	2873	2668	2567	2072	2072	2716	1272	6	213	1222
3	2477	2511	2579	2297	2916	2817	2383	1917	1917	2522	1194	0	212	1188
4	2244	2266	2605	2223	2733	2762	2262	1674	1674	2519	742	227	446	178
5	2350	2437	2601	2969	2454	2392	2022	1527	1527	2483	525	849	1062	107
6	2548	2748	2568	2437	2351	2363	1482	1373	1373	2383	31	327	472	66

	***i*=1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
7	2238	2317	2437	2224	2262	2308	2272	966	966	2219	1272	191	481	373
8	2194	2280	2255	2193	2189	2213	1990	811	811	2128	888	205	424	218
9	2297	2346	2214	2105	2001	2091	1719	373	373	1933	225	272	491	206
10	2300	2368	2033	2043	1851	2715	1683	322	322	262	73	307	527	297
11	2204	2308	2742	1324	1965	2455	1489	224	224	373	218	981	1170	231
12	2407	2438	2555	1951	1602	2263	1373	922	922	1919	1445	627	846	1219
13	2189	2266	2214	1224	1373	2019	1272	844	844	1373	1379	681	899	1373
14	2163	2199	2111	1916	1272	2076	1218	3	3	1071	542	759	978	1177
15	2839	2087	2033	843	987	1844	1029	1018	1018	1272	855	1071	1290	1408
16	2459	2955	1966	1244	946	1744	901	917	917	919	824	1144	1362	1383
17	2699	2139	1638	1414	1617	1452	848	718	718	272	631	1172	1391	919
18	2961	2081	1889	1557	1848	1322	752	806	806	4	872	1207	1466	839
19	3162	2206	2055	1637	1919	1255	572	1008	1008	3	324	1272	1491	941
20	2249	2546	1953	2	876	1552	698	1282	1282	1717	1060	1474	1693	1526
21	2297	2351	1431	91	182	1308	518	1272	1272	1951	1224	1557	1776	1683
22	1699	1779	1090	171	55	1218	307	1373	1373	2002	1197	1466	1685	1528
23	1644	1742	1267	835	184	1009	273	1019	1019	1882	999	1511	1730	1582
24	2076	1924	1230	1071	237	218	190	971	971	1583	885	1624	1846	1522
25	1633	1981	1079	1415	321	361	179	1182	1182	417	802	1635	1966	1417
26	1438	2192	1179	2199	962	417	11	1272	1272	363	794	1739	2295	1446
27	1068	1080	1198	188	213	1722	1272	1573	1573	1983	1419	2076	2546	2188
28	634	1077	1209	204	172	1345	911	1474	1474	1885	1583	2219	2466	2217
29	324	740	668	223	365	411	222	1562	1562	1363	1321	2113	2627	2159
30	624	1002	379	633	872	118	89	1639	1639	1681	1301	2282	1632	2264
31	901	833	449	466	1072	553	1	2030	2030	1183	1298	2286	2640	2068
32	1198	1211	1213	195	679	1722	1090	2033	2033	1673	1572	2295	2764	2329
33	102	330	1071	211	326	1326	918	2109	2109	1681	1527	2419	2372	2336
34	51	490	944	324	632	923	772	2219	2219	1369	1573	2479	2344	2308
35	921	190	99	842	1216	263	217	2383	2383	1471	1601	2427	2962	2219
36	871	211	2	902	1526	198	192	2437	2437	1272	1672	2519	1975	2188
37	88	529	1100	962	1016	1411	919	2582	2582	1908	1944	2419	2001	2419
38	210	902	772	939	964	1401	819	2683	2683	1881	1813	2227	2188	2674
39	324	320	528	982	1065	1187	617	2464	2464	1772	1919	2599	2272	2702
40	643	0	244	1100	818	917	780	2456	2456	1921	2002	2617	2373	2771
41	880	528	194	1214	1203	615	627	2563	2563	1451	1911	2627	2337	2802
42	1080	1024	101	1712	1458	342	996	2433	2433	1429	1684	2185	2402	2607
43	1419	1955	80	2059	1716	303	598	2022	3022	1664	1738	2456	2409	2628
44	1744	2036	7	2247	1356	272	398	3032	3032	1329	1718	2695	2573	2619

Table 3

The average of the drilling cost per meter.

LD_{ij}(m)	≤ 500	$500-1000$	1000-1500	1500-2000
K'_{ij}(US $)	122.49	177.63	249.69	296.93

The average drilling costs of vertical or horizontal wells can be different from each other. However, for approximately homogeneous and isotropic reservoirs and if any unexpected events do not occur, it can be assumed that these costs are constant. The model is solved by Balas algorithm. The answers (x_{ij} values) are obtained in accordance with Table 4. Table 5, which is taken from Table 4, tabulates the 44 proposed paths.

Table 4

The results obtained from the proposed model (x_{ij} values).

	***i*=1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
***j*=1**	0	0	0	0	0	0	0	0	0	1	0	0	0	0
2	0	0	0	0	0	0	0	0	0	1	0	0	0	0
3	0	0	0	0	0	0	0	0	0	1	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	1	0	0	0
5	0	0	0	0	0	0	0	0	0	0	1	0	0	0
6	0	0	0	0	0	0	0	0	0	0	1	0	0	0
7	0	0	0	0	0	0	0	0	0	1	0	0	0	0
8	0	0	0	0	0	0	0	0	0	1	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0	1	0	0	0
10	0	0	0	0	0	0	0	0	0	0	1	0	0	0
11	0	0	0	0	0	0	0	0	0	0	1	0	0	0
12	0	0	0	0	0	0	0	0	0	1	0	0	0	0
13	0	0	0	0	0	0	0	0	0	1	0	0	0	0
14	0	0	0	0	0	0	0	0	0	0	1	0	0	0
15	0	0	0	0	0	0	0	0	0	1	0	0	0	0
16	0	0	0	0	1	0	0	0	0	0	0	0	0	0
17	0	0	0	0	0	0	1	0	0	0	0	0	0	0
18	0	0	0	0	0	0	1	0	0	0	0	0	0	0
19	0	0	0	0	0	0	1	0	0	0	0	0	0	0
20	0	0	0	0	1	0	0	0	0	0	0	0	0	0
21	0	0	0	0	1	0	0	0	0	0	0	0	0	0
22	0	0	0	0	1	0	0	0	0	0	0	0	0	0
23	0	0	0	0	1	0	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	1	0	0	0	0	0	0	0
25	0	0	0	0	0	0	1	0	0	0	0	0	0	0
26	0	0	0	0	0	0	1	0	0	0	0	0	0	0
27	0	0	0	0	1	0	0	0	0	0	0	0	0	0
28	0	0	0	0	1	0	0	0	0	0	0	0	0	0
29	0	0	0	0	1	0	0	0	0	0	0	0	0	0
30	0	0	0	0	0	0	1	0	0	0	0	0	0	0
31	0	0	0	0	0	0	1	0	0	0	0	0	0	0
32	0	1	0	0	0	0	0	0	0	0	0	0	0	0

	i=1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
33	0	1	0	0	0	0	0	0	0	0	0	0	0	0
34	0	1	0	0	0	0	0	0	0	0	0	0	0	0
35	0	1	0	0	0	0	0	0	0	0	0	0	0	0
36	0	0	0	0	0	0	1	0	0	0	0	0	0	0
37	0	1	0	0	0	0	0	0	0	0	0	0	0	0
38	0	1	0	0	0	0	0	0	0	0	0	0	0	0
39	0	1	0	0	0	0	0	0	0	0	0	0	0	0
40	0	1	0	0	0	0	0	0	0	0	0	0	0	0
41	0	1	0	0	0	0	0	0	0	0	0	0	0	0
42	0	1	0	0	0	0	0	0	0	0	0	0	0	0
43	0	1	0	0	0	0	0	0	0	0	0	0	0	0
44	0	1	0	0	0	0	0	0	0	0	0	0	0	0

Table 5

The starting points (*i*) and the end points (*j*) of the optimal paths.

Rig number(*i*)	**Numbers of target points that are drilled by this rig (*j*)**
2	32,33,34,35,37,38,39,40,41,42,43,44
5	16,20,21,22,23,27,28,29
7	17,18,19,24,25,26,30,31,36
10	1,2,3,7,8,12,13,15
11	4,5,6,9,10,11,14

The graphical answer is shown in Figure 4. The rigs are shown with empty squares.

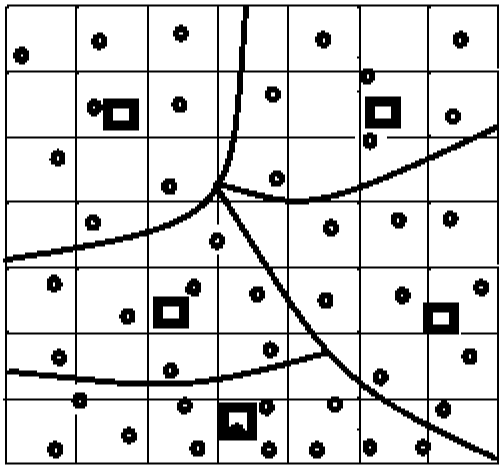

Figure 4
Locations of the drilling rigs and wells which will be drilled.

Moreover, the minimum objective function value and the cost reduction percentage will be as follows:

$C_{T,min}$ = US$ 1259.42 million, the contract value= US$ 1524.83 million, the cost reduction percentage = $[(1524.83 - 1259.42)/1524.83] \times 100 = 17.4\%$.

Obtaining a proper answer in this example does not mean that the model is in real situation; nonetheless, this model can be used in actual situations as a tool in drilling management.

5. Conclusions

One of the ways to reduce the drilling costs in oil and gas wells is to use directional drilling. The model can determine optimal well placement as well as optimal paths to develop the field. This model was used in the drilling network of an Iran southern gas field, and the drilling cost was decreased by 17.4%. The drilling executive conditions and restrictions of rigs play a major role in limiting relation setting. More exact models require more details such as the influence of drilling types, drilling depth, and other performance parameters, which are essential for a further study in this area. The registration fees and costs of drilling rig in the formation types with separate coefficients are useful to find the coefficients of the model. For this research, the cooperation of the industry is required. In general, the use of directional drilling in networks has led to a greater management complexity, and therefore, with a variety of models available, this model has been introduced to take advantage of simplicity.

Nomenclature

B	: Minimum number of rigs
C_{1n}	: Rig daily rental
C_{2n}	: Daily operating cost
C_n	: Rig daily costs
C_p	: Total cost of the drilling network
$C_{P_{ij}}$	: Cost of drilling from *i* to *j*
C_R	: Rigs cost
C_T	: Objective function
$\mathcal{D}_{ij}$	: Directional part cost
K	: Maximum number of rigs
K_{ij}	: Average cost per meter in vertical section
K'_{ij}	: Average cost per meter in directional section
LD_{ij}	: Directional length of drilling
LV_{ij}	: Vertical length of drilling
N	: Numbers of locations that allow installation of rig
S_i	: Cost of drilling rig *i*
t_n	: Days those rigs are used
V_{ij}	: Vertical part cost

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