A Commodity Production Model with Operational Flexibility of Investing Optional Capacity on Offshore Platforms

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***Abstract*— We study the problem of operational flexibility on capacity investment of an oil producer. Our decision-maker operates only on land fields and has option to extend operations to offshore oil platforms. The operational flexibility arises from the ability to invest on offshore fields. Our main goal is to integrate offshore platforms from the chemical and petroleum engineering literature, and capacity investment from operations management literature. We use a mixed integer programming solution approach and set a basic model to analyse the value of operational flexibility. Our main contribution is to provide an operational flexibility option to the problem of oil drilling.**

***Keywords*—** *Operational Flexibility; Capacity Investment; Supply Chain Management; Integer Programming*

1. Introduction

In the last past century the energy need of the global economy increased dramatically and the world economies have been very sensitive to the energy related issues such as dramatic volatility in oil prices. The literature on energy substantially increased after the energy embargo of OPEC in 1970s [4]. However, early studies focus on the optimization of oil wells and drilling decisions, in which heuristics methods are used to find a near-optimal solution. In a May 2006 energy market report from London-based broker Willis Group Holdings Ltd., Gulf of Mexico oil installations had $15 billion damages from Hurricane Katrina and Rita [7]. In addition to the loss of oil producers due to the disasters, the production stoppage risk is very significant; hence oil producers purchase insurance coverage despite owning large amount of capital and liquidity [7].

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In the US, a broad coalition of chemical producers and other US manufacturers have been trying to persuade the US Senate to access abundant oil and gas reserves in the outer continental shores of US coastlines and the production stoppages' impact on passing an offshore oil exploration bill [10]. However, the US senate passed a much narrower measure that would open a small portion of eastern Gulf to development for offshore platforms. Even if the US Senate agreed to open a small portion of abundant coastal areas, it will still have a significant impact on increasing offshore platform investments.

In addition to surge of offshore platforms, new technology for offshore wells enable to go deeper in the sea [5]. Moreover, UK and Norway are going to invest significant amount of resources on offshore platforms in North Sea due to great oil and gas reserves. Furthermore, Gazprom and Norsk Hydro signed a contract for 25 years to explore and invest offshore platforms on Shtokman field located at Barents Sea [13]. Considering these recent developments in offshore drilling, the impact of operational flexibility in oil drilling is very significant. In this study we provide integration of offshore platform drilling with operational flexibility perspective from operations management literature.

In our study, we want to answer two main questions: (1) what are the key factors in determining to invest a new oil well on land or offshore? (2) What is the value of operational flexibility? Our main contribution is combining the concept of operational flexibility option with oil drilling in the supply chain management literature. The rest of the paper is organized as follows: In Section 2, we review the related literature about oil drilling in offshore platforms from chemical engineering and operations management literature. Then, Section 3 presents our model with operational flexibility in offshore platforms and Section 4 discusses our numerical examples. We conclude our study with discussion on our results and future research directions in Section 5.

2. Literature Review

Problems on oil exploration and drilling processes are well studied in chemical and petroleum engineering literature. However, the studies in those fields are related to solving large-scale optimization problems and very specialized problems in a certain company. Oil production in offshore platforms is first presented as a minimum cost optimization [3]. In this seminal work, the problem is formulated as the minimum cost development of offshore fields, which is a well-known facility location problem and perform a computational study to evaluate performance of their model [3].

Additionally, Ref. [2] extends his previous work by allowing dual completion oil wells, which means that two oil targets are produced together through a single hole. Then, he formulates this problem as a matching problem. Besides these two initial models about offshore drilling, Ref. [12] lists the offshore field developments and focuses on engineering aspects of oil drilling, such as drilling trajectories and dual completions. In addition to the economic optimization of the offshore petroleum production, Ref. [6] studies the model after an offshore field with a producer whose objective is to maximize discounted after-tax cash flows subject to production constraints without any restrictions on transportation.

Regarding the objective of the decision-maker, we assume a profit maximizing oil producer. Ref. [14] states, " the objective of an oil company is not primarily the locating and sizing of platforms for oil production." Moreover, Ref. [10] studies the locating and sizing the offshore platforms for oil exploration by using multi-capacitated location problem and providing an exact solution and an approximate solution by a Tabu-search heuristic.

As for the recent about offshore platforms in chemical and petroleum engineering literature, Ref. [1] investigates oil-planning strategies by using Mixed-Integer-Linear-Program and provides real life dimensions of the problem. Further, Ref. [8] incorporates uncertainty to the decision process in oil field planning by using a two stage stochastic programming approach

3. The Model

Our general problem is a two stage stochastic programming approach with recourse. However, we will relax this assumption to provide managerial implications due to stochastic complexity of the problem. We assume that there are only two possible areas to make the oil platforms: Land or Offshore. Therefore, the decision-vector, $K_i \in \{0,1\}$, is.

$$K_i = \begin{bmatrix} L_i \\ S_i \end{bmatrix}, \qquad (1)$$

where i=1, 2 represents the stage of the problem. The oil producer decides her investment vector that decides to build well on land or offshore platform. In this problem setting, the operational flexibility is considered as having option to invest on an offshore platform; hence, S_i represents the flexibility in the problem. The oil producer's decision vector without the flexibility is $K_i=[L_i]$.

The notation of our problem is the following:

p: Price of the oil

d_L: Disaster risk in the land field, binary random variable

d_S: Disaster risk in the offshore field, binary random variable

f_L: Fixed penalty cost if disaster happens in the land field

f_S: Fixed penalty cost if disaster happens in the offshore field

c_L: Production rate in the land field

c_S: Production rate in the offshore field

F_L: Fixed capital cost to build oilrig on land

F_S: Fixed capital cost to build offshore platform

E_L: Fixed capital cost to abandon oilrig on land

E_S: Fixed capital cost to abandon offshore platform

In our problem, p, d_L, d_S, c_L and c_S are stochastic. Considering the decision tree of the stochastic program, the uncertainties in c_L and c_S are revealed after the first stage, but p, d_L and d_S will remain stochastic again. In the literature of modelling the disaster risk, Ref. [15] uses the periodic Poisson model to analyse the Texas Gulf Coast hurricane occurrences. In comparison with Ref. [15], our disaster parameter for land and sea will be different and can be in any general probabilistic approach.

The objective of our problem is to maximize the total profit over two stages. In oil exploration business for both land and offshore drilling, each stage is around 100 days [1]. Due to complexity of the problem, we will simplify our original problem by relaxing the stochastic programming approach, our problem becomes:

$$\max_{L_1,L_2,S_1,S_2} L_1\big(p_1 c_{L,1} - F_L - f_L d_{L,1}\big) + L_2\big(p_2 c_{L,2} - F_L d_{L,1} - f_L d_{L,2}\big) - (L_1 - L_2)E_L + S_1\big(p_1 c_{S,1} - F_S - f_S d_{S,1}\big) + S_2\big(p_2 c_{S,2} - F_S d_{S,1} - f_S d_{S,2}\big) - (S_1 - S_2)E_S$$

subject to

$$L_1 - L_2 \geq 0$$

$$S_1 - S_2 \geq 0$$

$$L_1 - S_1 \geq 0$$

$$L_2 - S_2 \geq 0$$

$$L_1, L_2, S_1, S_2 \in \{0,1\}$$

This problem formulation is a simplified version of our original model to capture the characteristics of the oil-drilling problem with operational flexibility.

4. Numerical Results

In this this section, we evaluate the value of operational flexibility in the commodity producer's oil dig problem. The fundamental questions we seek to answer are when it is managerially beneficial to invest on offshore fields. We also investigate the sensitivity of this operational flexibility with respect to model parameters, especially oil prices, production rates and disaster risk.

Considering the large number of parameters and the nature of oil digs, we assume industry averages for F_L, F_S, f_L, f_S, E_L and E_S. The cost of building oilrigs on land, F_L, ranges from \$1 and \$15 million and the average cost is around \$5 million. Similarly, the cost of building offshore fields, F_S, is between 15 and 100 million dollars and oil producers on average pay 30 million dollars [9]. Hence we set F_L to \$5 million and FS to \$30 million. Regarding the penalty costs due to disasters, f_L and f_S, the average cost to clean up after land disasters, f_L, is \$100 million, and the average cost to clean up after an offshore disaster, f_S, is \$161 million [16]. We use these two values as fixed cost of disasters for f_L and f_S. As for the abandonment costs for land oilrigs and offshore fields, E_L and E_S, oil producers generally account 10% of the building cost of the corresponding oil field. Thus we set, E_L and E_S as 10% of F_L, F_S, respectively.

In our experimental design, we focus on analysing the impact of operational flexibility on a oil producer's profit maximizing problem based on three major factors: price of oil (p_2 and p_1), disaster risk ($d_{L,1}$, $d_{L,2}$, $d_{S,1}$ and $d_{S,2}$) and the production quantities ($c_{L,1}$, $c_{L,2}$, $c_{S,1}$ and $c_{S,2}$). Our main goal is to investigate the sensitivity of the value of operational flexibility to the decision-maker in specific conditions.

4.1. Oil Prices

Our goal in this section is to investigate in which situations the oil producer should take advantage of the operational flexibility to invest in offshore fields. Is high oil price enough to explore offshore options? What if oil production is too low in offshore platforms? What should the oil producer do if disaster risk is reasonable?

Besides our assumptions described above, we assume production rate of 1 million barrels for land ($c_{L,1}$ and $c_{L,2}$) and 0.5 million barrels for offshore option ($c_{S,1}$ and $c_{S,2}$) in the base experiment. Then the price of oil per barrel will be from the set of these prices: \$30, \$90, \$120 and \$200. The oil price barrel has been over \$90 in the last two years and \$30 and \$200 are extreme cases. Table 1 shows our experimental design to investigate the impact of oil prices on the oil producer's decision to invest on the operational flexibility. In the case of no disaster risk, offshore fields are valuable for the oil producer except when the oil price is historically low, \$30. This result is intuitive since revenues outweigh the operational, building and abandonment costs. If there is a disaster on land in the first stage of the problem, oil producer still continues to invest on both land and offshore platforms for higher values of the oil price. However, if oil price is low, $30, investing on neither land nor offshore platforms is optimal because of the high penalty costs of disaster and other operational related costs.

Table 1. Impact of the oil price

p_1	p_2	(L_1, L_2, S_1, S_2)	*Profit**	$(d_{L,1}, d_{L,2}, d_{S,1}, d_{S,2})$
$30	$30	(1,1,0,0)	$55M	(0,0,0,0)
$90	$90	(1,1,1,1)	$235M	(0,0,0,0)
$120	$120	(1,1,1,1)	$325M	(0,0,0,0)
$200	$200	(1,1,1,1)	$565M	(0,0,0,0)
$30	$200	(1,1,1,1)	$310M	(0,0,0,0)
$200	$30	(1,1,1,1)	$310M	(0,0,0,0)
$30	$30	(0,0,0,0)	$0	(1,0,0,0)
$90	$90	(1,1,1,1)	$130M	(1,0,0,0)
$90	$90	(1,1,0,0)	$70M	(1,0,1,0)
$200	$200	(1,1,0,0)	$290M	(1,0,1,0)
$30	$30	(0,0,0,0)	$0	(1,1,1,1)
$90	$90	(0,0,0,0)	$0	(1,1,1,1)
$120	$120	(1,1,0,0)	$30M	(1,1,1,1)
$200	$200	(1,1,0,0)	$190M	(1,1,1,1)

As for the disaster risk on offshore platforms, the oil producer avoids investing on this operational flexibility option due to high cost of penalty. The penalty cost for offshore platforms can easily exceed the average cost of $161 million. For example, the recent BP oil spill cost is over $40 billion. Hence the oil producer should take advantage of this operational flexibility to explore offshore fields if oil price is high and there is minimal risk of disaster.

4.2. Disaster Risk

In this section we analyse the impact of disaster risk on oil producer's decision to use offshore platforms. We set the oil price at $90 because we already investigated the relationship with the oil price and the disaster risks. The results shown in Table 2 are robust when the price of oil is either $120 or $200 per barrel. However, we also want to see whether the oil producer would be interested in the offshore fields if the yield were not high enough. Thus we investigate the relationship between the oil production rates from the offshore platforms and disaster risks.

Table 2. Impact of the disaster risk

$(d_{L,1}, d_{L,2}, d_{S,1}, d_{S,2})$	$c_{L,1}, c_{L,2}$	$c_{S,1}, c_{S,2}$	(L_1, L_2, S_1, S_2)	*Profit**
(0,0,0,0)	1M	0.5M	(1,1,1,1)	$235M
(0,0,0,0)	1M	1M	(1,1,0,0)	$175M
(1,0,1,0)	1M	0.5M	(1,1,0,0)	$70M
(1,1,1,1)	1M	0.5M	(0,0,0,0)	$0
(1,0,1,0)	1M	2M	(1,1,1,1)	$209M
(1,1,1,1)	1M	2M	(0,0,0,0)	$0
(0,0,0,0)	0.1M	2M	(1,1,1,1)	$343M
(1,0,1,0)	0.1M	2M	(1,1,1,1)	$470M
(1,1,1,1)	0.1M	2M	(0,0,0,0)	$0

Table 2 shows that oil production rate plays an important role for the oil producer in investing the offshore fields. Besides higher oil prices, considering the operational flexibility is beneficial for the decision-maker when the oil yield from offshore platforms is significant compared to the penalty cost if a disaster happens.

4.3. Oil Production Rates

The operational flexibility is important for the oil producer due to uncertain production yields and high oil prices. In this section, we investigate how oil production rates in offshore platforms affect the value of the operational flexibility option for the decision-maker. Moreover, we set the disaster risks to be zero to ignore its impact on the value of the operational flexibility.

Table 3. Impact of the oil production rates

$c_{L,1}, c_{L,2}$	$c_{S,1}, c_{S,2}$	p_1, p_2	(L_1, L_2, S_1, S_2)	*Profit**
1M	0.5M	$30	(1,1,1,1)	$55M
100000	0.5M	$30	(1,1,1,1)	$1M
0	0.5M	$30	(0,0,0,0)	$0
80000	0.5M	$30	(0,0,0,0)	$0
0	0.5M	$200	(1,1,1,1)	$165M
1M	0	$90	(1,1,0,0)	$175M
1M	100000	$90	(1,1,0,0)	$175M
1M	100000	$200	(1,1,1,1)	$405M

Higher oil production rate of the offshore option is beneficial for the oil producer even with cheap oil prices. However, any lower production rate from land oilrigs force not to seek the operational flexibility due to our problem setting. This makes sense because the oil producer's main business is on land. Hence lower production rates on land with low oil prices force the oil producer not to invest on offshore platforms. On the other hand, higher oil prices allow the oil producer take advantage of the offshore platforms even if there is little oil production from land oil fields.

5. Conclusion

In this paper we model the operational flexibility as a capacity investment on offshore platforms for an oil producer. The oil producer primarily drills oil from land and considers the offshore option as an additional capacity investment. We use a mixed integer programming approach to relax the stochastic nature of this problem in order to gain more tractability for managerial implications. Our main contribution in this study is to present an operational flexibility option for an oil producer who operates generally on land.

Our numerical results show that the operational flexibility is very beneficial for the oil producer when the oil price is higher (especially when it is higher than $90). However, this benefit can easily be overcome by the risk of disaster. Even if the historical average cost of several hundred million dollars, the penalty cost for offshore platforms can exceed tens of billion dollars. An oil producer needs to be very diligent about the risks of these offshore platforms and follow extreme safety measures. Moreover, we showed that oil production rates, especially in offshore platforms, have a significant impact on the value of the operational flexibility option for the oil producer. As long as the oil prices are high enough and there is minimal disaster risk, the production rates on offshore platforms have minimal effect on not investing on the operational flexibility. However, lower oil production rates on land and low oil prices make the operational flexibility a bad investment option for the decision-maker.

In this study, we modelled an oil producer's problem with the introduction of the operational flexibility, which is a capacity investment on offshore platforms. We simplified the complex problem into a mixed integer program to provide helpful managerial insights to help the strategic decision-making process in oil drilling industry. The limitation of our study is not incorporating the stochastic nature of the problem. Modelling the problem as a two-stage stochastic programming is our future work to extend our base model.

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