Title: Uncertain time to completion in a sequential investment problem: a theoretical and empirical analysis

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Extended abstract

Investment towards oil production is a complex step-wise process, from exploration, appraisal of oil reserves, development of oil fields and support infrastructure, actual production of oil to decommissioning. The exploration stage involves site surveys for potentially viable oil reserves. The oil company makes investments towards exploration drilling and estimation of reserves and potential production. At this stage the firms are faced with high uncertainties of the existing reserves. If no potentially viable reserves are discovered, the project is abandoned. Where potentially viable oil sources are discovered, further exploration is undertaken, leading to the appraisal of the oil sites. At the appraisal stage, exploration wells are drilled to discover and map the oil reserves. Where oil reserves are confirmed to be commercially viable, the oil companies proceed to prepare to develop the site. The development phase involves significant investments towards well drilling, construction of production facilities, roads, oil pipelines, terminals, in preparation of actual oil production. The production stage is the stage at which that oil companies and host governments realise a profit on their investment from actual extraction and sale of oil. The production phase commonly lasts from 20-30 years from the first oil to abandonment. Over this period, production may vary depending on available reserves, the number of active wells, oil price and extraction technology. Once it is no longer economically viable to extract the remaining oil reserves, the site is decommissioned. This final stage involves plugging oil wells, site remediation and removal of facilities and equipment with the aim to restore the site to its original state, as close as possible.

Investments at each sequential stage of oil project lifecycle are highly costly, lumpy and are sunk, for the most part, once expended. More so, each successive stage prior to the production stage typically does not lead to immediate cash flows but opens up further investment opportunities. The capital intensity of oil investments, particularly at the development stage,

makes them irreversible because the oil wells and operation facilities can only be used to produce oil. These complexities are exacerbated by the various uncertainties faced by these projects. Among these is the uncertainty about the oil price which significantly influences the value of an oil project. Another is the uncertain time to completion of the preceding stages to production stage, particularly the development stage that requires large capital-intensive investments in oil drilling facilities and support infrastructure that take a long time to build.

The inherent sequentiality in oil projects offers increased flexibility in allocation of resources, depending on how these uncertainties revolve over time. Real options methods have been applied to analyse option-like flexibility and value/uncertainty relationship, in the context of sequential investment projects. McDonald (1986) examine the optimal timing of an irreversible investment project where the project value and the final investment cost both are dependent on stochastic variables. The variables follow a stochastic geometric Brownian motion (GBM) process, and the authors derive an optimal investment rule and a formula for valuation of the project. Their main findings are that the option to wait increases project value, and that it is optimal to postpone the final investment until the project value is twice the size of the investment cost. McDonald (1986), however, ignore sequentiality of such complex investments. Majd & Pindyck (1987)} analyse sequential construction projects by using contingent claims analysis to derive optimal decisions rules and values of investments with irreversible cash outlays and maximum construction rates. Their study presents the effects of time to build, opportunity cost and uncertainty on the investment decision. Their findings suggest that time-to-build have greatest impact on the investment decision when uncertainty is greatest. Their study also examines the economic value of construction time flexibility and find that the value of the investment project rises as the minimum construction time shortens. Cortazar & Schwartz (1993) provide analytical expressions for valuing a firm operating under two sequential stages, each with a different output capacity. Their study analyses the effects of price volatility and interest rates on firm value, optimal production and optimal inventory levels. Their findings show that an increase in the risk-free rate raises the critical spot price of the second stage. They also find that increases in the spot price volatility and in the risk-free interest rate decreases the first stage critical spot price. Dixit (1994) formulate a model for a two-stage investment that can be applied to a wide range of contexts under sequential investments. The model can be used to develop an investment rule to solve for threshold oil prices and project values.

Cortazar (1997) apply finite difference methods to solve for the value of an undeveloped Chilean oil field, that undergoes three stages (i.e., before committing to investment of development phase; development of the oil fields and actual oil production). The study assumes that the oil price follows a mixed GBM and mean-reversion (MR) process. Their findings identify a critical spot price that triggers development of the field. The critical price lowers as the time to expiry of the delaying option shortens. They find that the value of the option to delay development investment decreases as the oil price increases. Huisman (2015) develop a stochastic dynamic duopoly framework to analyse investment timing and capacity decisions of firms, where undertaking the investment implies obtaining a production plant. They assume a linear demand function that follows a GBM process. In line with standard real options theory, they find that increased uncertainty about demand raises the optimal investment threshold and thus delays investment. They also find that increased uncertainty incentivises overinvestment as an entrance deterrence strategy. Building on the model by Ketelaars (2019) recognises sequentiality and uncertainty of time to completion of R&D investment projects. The study assumes a poisson process to model uncertainty of innovation break-through. The author relies on numerical proofs to show that a firm invests more in the first stage R&D stage to innovate sooner if it observes a higher price. Adding running costs to the analysis, the study finds that the firm invests less in R&D for each price. In consideration of the abandonment option, the author finds that investing more in R&D implies more costs and hence it is optimal for the firm to exit at a higher price. As regards, the option to defer the R&D investment, it is more likely that the firm immediately launches the new product upon innovation, when the price is above the product launch threshold. In line with standard real options theory, the study finds that increased market uncertainty causes the firm to delay R&D investment project and increases the likelihood of abandoning the project before innovation. Similar to Huisman (2015), the study also finds that the firm overinvests with increased uncertainty.

A few authors add the dimension of uncertainty about time to completion to study sequential irreversible investments. Miltersen & Schwartz (2007) develop a real options valuation framework to derive closed form solutions for the value of a two-stage project and optimal abandonment and switching thresholds, with uncertain time to completion of the first stage. The time to completion is governed by an independent exponential distributed random variable, such that the value of the project is expressed as a solution to an ordinary differential equation. Their study assumes that the owner of the project pays on-going costs per unit of time until the first stage is completed, and these costs are uncertain. They also assume that the value of the investment project follows a GBM process. The authors found that, for realistic values of on-going costs, the value of the investment project decreases with longer expected time to completion. However, for very low values of on-going costs, their results show that the value of the investment project increases in the expected time to completion. They also demonstrate that the abandonment thresholds are a non-monotonic function of the expected time to completion and that the switching thresholds increase with lower on-going investment costs and longer expected times to completion. Similar to Huisman (2015), Miltersen & Schwartz (2007)} also extend their analysis to a duopoly case, which is beyond the scope of our study. Our study is specifically applied to oil investment projects, which are often structured in a way that an oil company has monopoly rights to the contract area over which it operates.

Helland & Torgersen (2014) extend the Miltersen & Schwartz (2007) model in which they present an analytical real options model for evaluating the exploration stage of a petroleum investment project with uncertainty of the oil price, exploration costs and the time to completion of the exploration. Time to completion of the exploration stage is modelled as a Poisson process. From the closed form solutions, they can compute the value of the investment option when the project owner has the flexibilities of abandoning and delaying the investment upon completion of the exploration stage. They find that decreasing the expected time to completion of the exploration stage increases the value of the project at all oil prices, and consequently reduces the abandonment threshold level.

In our study we present a real options framework for evaluating the development stage of a petroleum investment project with uncertain time to completion. Based on the cost of development, the oil price, and expected time to completion of the development phase, we estimate the value of the irreversible option to invest in the development stage. Accordingly, we find optimal oil price threshold levels for investment at the development stage and production stage.

This work adds to the literature by incorporating both sequentiality and uncertainty about time to completion of the development stage. The model setup is developed in the context of oil investments, however, it may be applied to other investment problems in commodities, such as mining for precious or base metals, and natural gas fields.

In addition to the theoretical analysis the theoretical results are applied on the Ugandan Albertine Graben project. Project data are used as input values and numerical results are computed. Numerical analyses are carried out to determine how project values and threshold prices are affected by changes in input parameter values. This includes amongst other changes in oil price characteristics, i.e., drift and volatility rate, expected duration of development stage, investment amounts, operational expenditures, and production quantities.

Some of the findings are as follows: Oil price drift rate has large impact on project values and the threshold price when to start development stage. Oil price volatility rate has significant impact on threshold prices and on project values when oil prices are relatively low. Expected development time has relatively low impact on project values and threshold prices when relatively short. For longer expected development time an interesting result is found. In case of low oil price drift rate, the longer the expected development time the higher the threshold price. In case of higher oil price drift rate, the longer the expected development time the lower the threshold price. This is further analysed in the paper.

In the Albertine Graben investment case the first investment decision, i.e., when to enter the development stage, requires much more investment capital then the second, which decide when to enter production stage. This typically gives that the first threshold price is much higher than the second threshold price. The paper also alters the investment amounts to analyse under which circumstances the second threshold price is higher than the first threshold price, and the numerical results are compared with the theoretical results