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Journal of Economic Dynamics & Control

journal homepage: www.elsevier.com/locate/jedc

An optimal multiple stopping approach to infrastructure investment decisions

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ARTICLE INFO

Article history:

Received 12 February 2013

Received in revised form

1 February 2015

Accepted 3 February 2015

Available online 11 February 2015

JEL:

C41

G13

H54

Keywords:

Optimal multiple stopping

Real option

Infrastructure investments

Lead time

Operational flexibility

ABSTRACT

The energy and material processing industries are traditionally characterized by very large-scale physical capital that is custom-built with long lead times and long lifetimes. However, recent technological advancement in low-cost automation has made possible the parallel operation of large numbers of small-scale and modular production units. Amenable to mass-production, these units can be more rapidly deployed but they are also likely to have a much quicker turnover. Such a paradigm shift motivates the analysis of the combined effect of lead time and lifetime on infrastructure investment decisions. In order to value the underlying real option, we introduce an optimal multiple stopping approach that accounts for operational flexibility, delay induced by lead time, and multiple (finite/infinite) future investment opportunities. We provide an analytical characterization of the firm's value function and optimal stopping rule. This leads us to develop an iterative numerical scheme, and examine how the investment decisions depend on lead time and lifetime, as well as other parameters. Furthermore, our model can be used to analyze the critical investment cost that makes small-scale (short lead time, short lifetime) alternatives competitive with traditional large-scale infrastructure.

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1. Introduction

The energy and material (e.g. water and petrochemicals) processing industries are traditionally characterized by very large unit-scale physical capital. For example, individual electric power generators rated in the 100s of MW, distillation towers in refineries measuring 100,000s of barrels-per-day of capacity, and mining trucks capable of hauling 400 tons of ore are common sizes in their respective industries. However, the recent emergence of low-cost automation technologies makes a modular, small-scale, and potentially distributed approach possible with comparable aggregate production capacity. This calls for a re-examination of the current “bigger-is-better” paradigm. Indeed, abandoning *economies of unit scale* in favor of *economies of mass-production* presents several opportunities, as discussed in Dahlgren et al. (2013). In contrast to the very long lifetimes of 25 years or more for typical large-scale capital, small and mass-produced equipment might be endowed with a much shorter physical lifespan. This could be either by design in construction or in operation with a limited maintenance schedule. Furthermore, with a smaller unit scale comes the ability to build to stock and drastically shorten lead

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times between the investment and operation. These factors provide the firm with additional flexibility to engage and disengage a given activity, which should be accounted for in the investment valuation and decision.

Motivated by this anticipated paradigm shift, we introduce here a framework that incorporates operational flexibility, lead time, capital lifespan, and multiple (finite/infinite) future investment opportunities. To this end, we formulate an optimal multiple stopping problem, where the firm maximizes the expected discounted reward from sequential investments. In particular, the project's reward function captures the operational flexibility of temporarily suspending production to avoid negative cash flows. Additionally, it depends explicitly on two crucial elements, namely, lifetime and lead time. Under capacity constraint, the firm's consecutive investments are separated (or refracted) by the capital lifetime. Hence, the firm's investment decision bears similarity to the valuation of a forward-starting swing call option written on the reward.

Our main result is the characterization of the firm's value function and optimal stopping rule. The optimal timing for multiple investments is described by a sequence of critical price thresholds. Furthermore, these thresholds are shown to be decreasing and converge to that corresponding to the case with infinite investment opportunities. Our analysis lends itself to an iterative algorithm that numerically solves for the optimal value function and all exercise thresholds, as opposed to the simulation approach commonly found in existing literature for swing-type options (Meinshausen and Hambly, 2004; Chiara et al., 2007; Bender, 2011). We examine the impacts of lead time and lifetime, as well as other parameters, on the investment decisions. Moreover, our model is also useful for analyzing the critical investment cost that makes small-scale (short lead time, short lifetime) alternatives competitive with traditional large-scale infrastructure.

As is well known, the real option approach to investment decisions can increase the project value above and beyond those rooted in classical net present value (NPV) arguments (Sick and Gamba, 2010; Dixit and Pindyck, 1994). In its inherent myopia, the NPV approach falls short of capturing the flexibility of timing since it, at best, only gives the decision maker an indication of whether or not a single investment should be made at the current time. Standard real investment option analysis addresses this limitation. Examples of the implementation of such an analysis regarding individual investment decisions can be found in, among others, Kaslow and Pindyck (1994), Frayer and Uludere (2001), Lumley and Zervos (2001), Carelli et al. (2010) and Westner and Madlener (2012). Nevertheless, the valuation of multiple consecutive investments has not received a great deal of attention in the industries in question. In the current paradigm, the individual investment is typically both large and long-lived, so the firm's next investment decision, including capacity replacement, will be an issue of the far future. With such a long horizon, discounting would reduce future cash flows to minimal present values. However, with shorter lead times and lifetimes, future investments can potentially have significant bearing on current capital budgeting decisions, as we will show in this paper.

Our valuation approach accounts for multiple and possibly infinite future investment options, which in turn allows for a comparison of capital investments with different lifetimes. To illustrate, let us compare two projects with different lifetimes, namely, one with 10 years and another with 3 years. To address the difference in investment horizon, one approach would be to consider a longer horizon of 30 years, the smallest common multiple of 3 and 10, and compare the corresponding net present values. However, this method implicitly assumes seamless consecutive investments at the end of each lifetime. This may not be optimal to the firm since it ignores the embedded timing option in each investment decision.

Another feature of our valuation framework is to incorporate the flexibility to delay future investments depending on market conditions. Another advantage over the pairwise comparison is that we can easily examine how sensitive the investment timing is with respect to different model parameters, especially for all lead times and lifetimes. We do acknowledge that durability of capital is a path-dependent variable, leading to a variable lifetime. In contrast, our approach uses a fixed lifetime independent of the frequency of operation, and it may favor the posited status quo of capital with a longer prescribed lifetime. Our choice of a fixed lifetime, albeit a simplification, results from the trade-off between model tractability and realistic details.

The use of swing options has been most prevalent in energy delivery contracts where the holder has the right to alter, or 'swing', volumes up or down at the start of each time period (Jaillet et al., 2004; Deng and Oren, 2006). Rather than fixed-period contracts, the only constraint on the timing in our setting is a minimum refraction time between consecutive investments. As such, the valuation of the swing contract can be formulated as a refracted optimal multiple stopping problem (see e.g. Carmona and Touzi, 2008; Carmona and Dayanik, 2008). Other financial applications involving multiple exercises include employee stock option valuation (Leung and Sircar, 2009; Grasselli and Henderson, 2009), and the operation of a physical asset (Ludkovski, 2008).

This paper is structured as follows. In Section 2 we introduce the investment decision as a general optimal multiple stopping problem. We also introduce a reward function that incorporates the flexibility to temporarily shut down production to avoid a negative cash flow. In the following section we state and prove sufficient conditions on a general reward function for the multiple stopping problem to have a well defined stopping boundary. We also present an algorithmic approach to finding the solution. In Section 4 we further motivate and analyze the specific reward function in the context of basic infrastructure investments and present numerical results. These results include a comparison of investment scenarios with short lifetimes and short lead times vs. a traditional scenario with comparatively long lifetimes and lead times. Finally, concluding remarks and potential extensions are discussed in Section 5.

2. Problem formulation

We consider a firm that has the ability to invest in capital equipment that produces a single good in a given market. Furthermore, we assume that this firm is acting as a price taker in this market, with a finite capacity constraint.

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