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Uncertainty and the trade-off between scale and flexibility in investment

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ABSTRACT

This paper analyzes the behavior of a firm that chooses both the scale and timing of its investment. Sensitivity analysis shows that greater demand volatility is associated with the firm investing in larger increments, less frequently. This is in contrast to the conventional wisdom, which is that greater volatility leads to investment in smaller increments, more frequently. Overall, the reduced frequency dominates the greater scale, so that the long-run average rate of investment is a decreasing function of demand volatility. The timing and scale of investment are most sensitive to volatility when there are substantial investment economies of scale.

1. Introduction

Firms contemplating investment in physical capital are often confronted with a trade-off between economies of scale and the flexibility afforded by investing in small increments as and when they are needed. Economies of scale encourage a firm to group several expansions into a single investment, as this can lower the present value of capital expenditure and raise the firm's market value. However, this exposes the firm to the risk that demand growth is not as strong as forecast, leaving the firm owning capital that it does not need. The optimal trade-off depends on many factors, including the extent of economies of scale and the volatility of demand. The conventional wisdom is that the presence of uncertainty means that the firm should invest in smaller steps, and more often, than would be the case if there was no uncertainty.[1] This paper shows that the conventional wisdom is not correct, using a simple model of the scale–flexibility trade-off in which greater volatility leads the firm to invest in bigger steps and to invest less often. This result is important because the extensive real-options literature on the relationship between investment and uncertainty pays little attention to the trade-off between scale and flexibility, despite economies of scale being an important characteristic of much investment in physical capital.[2] In order to understand the effect of uncertainty on investment we need to know how it affects firms' utilization of economies of scale, and that is this paper's focus.

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[1] See, for example, Section 2.5 of Dixit and Pindyck (1994). An important early exception is Manne (1961), who shows that a cost-minimizing firm that must meet exogenous demand will invest in larger steps when demand volatility increases.

[2] See, for example, the survey by Carruth et al. (2000).

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The firm faces exogenous demand shocks. Its level of production is restricted by the capacity of its physical capital, which is a continuous variable that changes over time as the firm invests in new capacity and as existing capacity deteriorates. There are economies of scale in investment, and the firm chooses the scale, as well as the timing, of investment. When choosing investment scale, the firm considers the required capital expenditure, the value of real options created and destroyed by investment, and the effect of new capacity on the value of the firm's assets-in-place (as greater capacity might lower the output price and thereby lead to some cannibalization). Sensitivity analysis shows that the firm responds to higher demand volatility by raising the scale of expansion. As a result, greater volatility leads to investment being lumpier: individual acts of investment occur less frequently, and involve larger additions to capacity, when volatility rises. This is the opposite result to the "conventional wisdom" of real-options analysis.

This result can be understood in terms of the direct and indirect effects of greater demand volatility on the optimal scale of investment. The direct effect of greater volatility is that the firm expands in smaller increments, *holding the timing of investment constant*. This occurs because higher volatility raises the downside risk of large-scale expansion relative to small-scale expansion without raising upside risk by enough to compensate. If demand growth is lower than expected, then the net operating income from the new capacity may be insufficient to cover the capital expenditure, and the shortfall from a large-scale expansion will be much greater than from a small-scale one. If demand growth is higher than expected, then the firm can build additional capacity if the scale of the initial expansion was too modest. This will be costly, as the firm has lost the opportunity to exploit economies of scale and build the additional capacity as part of its current expansion, but the cost will be small relative to the cost of building too much additional capacity when demand growth is lower than expected.

Greater demand volatility also affects the optimal scale indirectly, via its effect on the firm's investment timing. The value of delaying investment is higher, so the firm sets a higher investment threshold, *holding the scale of investment constant*. This changes the trade-off between scale and flexibility by reducing the costs of "overinvesting" in additional capacity—that is, even if demand growth is lower than expected after expansion, the higher investment threshold means that the firm may still be able to recover the capital expenditure incurred. The firm responds by taking greater advantage of economies of scale and raising the scale of each capacity expansion. Numerical analysis shows that the indirect effect dominates the direct one, so that greater demand volatility induces the firm to invest in larger increments, and to invest less frequently.

This paper contributes to the theoretical literature on the relationship between investment and uncertainty. The standard investment-timing model, due to McDonald and Siegel (1986), features a firm that invests as soon as the value of the (at that stage hypothetical) completed project reaches a particular threshold. The threshold is an increasing function of volatility, so that greater volatility makes the investment test more demanding. Some authors have taken this model and examined the sensitivity of alternative measures of investment activity to volatility. For example, Sarkar (2000) considers the probability that investment will occur within a specified time, and Wong (2007) analyzes the expected time until investment occurs. Other authors have modified the investment technology. For example, Kandel and Pearson (2002) introduce a reversible alternative investment alongside the usual irreversible one, whereas Blazenko and Pavlov (2009) cap the rate at which a firm can expand its physical capital, and in both cases greater volatility can relax the investment threshold. Still other authors have developed competitive-equilibrium models that allow them to analyze the relationship between volatility and industry-wide investment behavior. For example, Guthrie (2010) demonstrates that greater demand volatility can reduce the probability of investment in a specified period, while increasing the rate of any investment that does occur. The current paper uses a rich model of firm-level investment to yield insights into the effect of volatility on the frequency and scale of investment. By endogenizing scale, in particular, it investigates aspects of investment that are important in practice but have been under-analyzed in the literature.

Although there is an extensive theoretical literature on the link between uncertainty and real investment, much less is known about the relationship between uncertainty and the trade-off between scale and flexibility. An early example, Manne (1961), considers the problem facing a cost-minimizing firm that needs to expand its capacity over time in order to meet growing demand. He finds that the firm chooses a greater scale of investment when demand volatility rises. However, because Manne's demand level is exogenous, his model cannot predict how the firm would respond to changes in volatility when its objective is to maximize its market value and its demand is price responsive. The basis of the more recent studies of the scale–flexibility trade-off is a model of sequential investment in which a firm must complete two discrete stages of investment (Dixit and Pindyck, 1994, Chapter 10). Both stages are completed simultaneously in the basic model, but Bar-Ilan and Strange (1998) allow for time to build and find sequential investment is optimal. However, the firms in these models have no alternative to completing the two stages in sequence, preventing investigation of the scale–flexibility issue. Recently, Kort et al. (2010) have adapted the two-stage approach and examined the impact of volatility on the trade-off between scale and flexibility. In their model, a firm chooses between investing in a project with fixed capacity in one (relatively low-cost) or two (relatively high-cost) steps. The cost advantage needed to justify single-stage investment is a decreasing function of volatility, so that investing in a single stage becomes more attractive as volatility rises. In contrast to Kort et al. (2010), the model used here endogenizes the scale of investment, allows for an arbitrary number of stages of investment, and recognizes that expansion can cannibalize a firm's existing assets.

The model that is closest to the one in this paper is due to Cooper (2006). Like the one used here, it features a firm with a capital stock that is a continuous variable and is adjusted in discrete steps. Each time the firm invests it pays a constant price for each unit of capital installed and, in addition, a fixed lump-sum adjustment cost that is proportional to the profit flow at the investment date. This cost formulation is mathematically convenient and is interpreted as production being interrupted while the new capacity is installed. However, the process by which the continuous flow