Flexible Production Technology, Systematic Risk, and Stock-Level Investment Anomalies*

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Abstract

We offer empirical evidence that the investment anomaly (the tendency of high real-investment stocks to underperform others) is driven by firms building rather than acquiring extra capacity. We rationalize this finding using a real options model of the firm in which building implies that extra capacity becomes operational only after a construction period ("time-to-build"), but can ultimately be more dynamically reconfigured to respond to customer demands ("capacity flexibility"). The greater flexibility means that firms deciding to build extra capacity observe declines in their expected returns, which revert as the newly-built capacity ages and loses its extra flexibility. Further empirical work supports our assumption that newly-built capacity enables firms to react more flexibly to demand shocks.

Key words: Asset pricing; real options; investment anomalies; flexible capacity; time-to-build.

JEL classification: G11, G12, G15.

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1 Introduction

Empirical work suggests that the stocks of firms investing into extra production capacity yield low mean future returns compared to those of non-investing firms, with the low returns however reverting back to pre-investment levels after a couple of years ("investment anomaly"). See, for example, Titman et al. (2004), Anderson and Garcia-Feijóo (2006), Fama and French (2006; 2008), Cooper et al. (2008), and Xing (2008).[1] To illustrate these findings, Figure 1 plots the mean returns of portfolios containing the stocks of firms whose investment in year $t-1$ is above the fourth (green bars) or below the first (brown) quintile over years $t+1$ to $t+6$.

We offer empirical evidence that the investment anomaly is driven by firms building rather than acquiring extra productive capacity. To do so, we study the anomaly separately for firms engaged in construction work over the investment period and other firms, demonstrating that only the firms engaged in construction work produce a strong and highly significant anomaly. We rationalize these findings using a real options model of the firm in which newly-built capacity takes time to become operational ("time-to-build"), but can ultimately be more easily reconfigured in response to customer demands ("capacity flexibility"). The greater flexibility acts as insurance against the chance that customers lose interest in a firm's products, lowering the firm's systematic risk. As newly-build capacity, however, ages and becomes less able to accommodate customers' ever-evolving demands, systematic risk slowly increases again. We finally offer empirical evidence supporting that newly-built capacity does indeed allow firms to become more flexible.

Measuring investment as the scaled change in gross property, plant, and equipment (PPE) over the fiscal year ending in calendar year $t-1$, we first show that portfolio sorts and Fama-MacBeth (FM; 1973) regressions run over the 1986 to 2016 period yield a significantly negative investment premium, confirming that our data and variable definitions produce an investment anomaly.[2] We

[1]Motivated by these findings, Fama and French (2015) and Hou et al. (2015) develop linear factor models including an investment-based factor long non-investing stocks and short investing stocks. Given their evidence that the factor explains value, accruals, investment, leverage, and external financing anomalies, we believe that it is important to shed further light on why investment conditions stock returns.

[2]The sample period for our empirical work is motivated by the availability of our construction-work proxy.

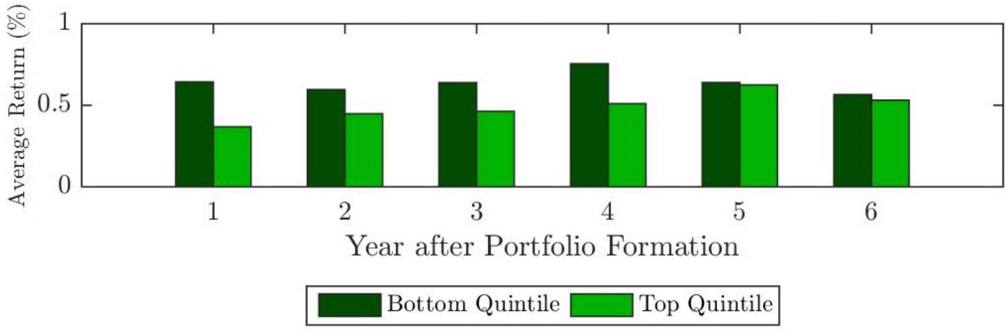

Figure 1: Mean Returns of Investing and Non-Investing Stocks In this figure, we plot the mean monthly returns of top and bottom investment quintile stock portfolios over the years after portfolio formation. We sort stocks into portfolios in June of year t, using the change in gross property, plant, and equipment over the fiscal year ending in calendar year $t-1$ scaled by total assets at the start of that fiscal year as sorting variable. We value-weight the portfolios and hold them from July of year $t+(x-1)$ to June of year $t+x$, where x is the number shown on the x-axis. The sample period underlying the figure is 1967 to 2016.

next note that U.S. accounting rules mandate that expenses associated with construction activity have to be reported in a gross PPE subaccount ("PPE-CIP") during construction, allowing us to identify those investing firms for which construction is at least partially responsible for their PPE increases. Separately studying firms with a zero and positive PPE-CIP balance at the end of the investment period, we find that the investment anomaly only exists among firms with a positive balance. The portfolio sorts, for example, suggest that the spread portfolio long the highest value-weighted investment decile and short the lowest yields a mean return of –10.36% per annum (t-statistic: –3.09) among the stocks of firms building new capacity, but a mean return of only –3.98% (t-statistic: –1.30) among others. The FM regressions show that the investment anomaly is 1.61% per month lower for building rather than non-building stocks (t-statistic: –2.92). Using cumulative returns, we find that these results are also economically important.

We use an extended version of Pindyck's (1988) real options model of the firm allowing for time-to-build and flexible capacity to rationalize our empirical results (see also Carlson et al. (2004); Cooper (2006); Hackbarth and Johnson (2015); and Aretz and Pope (2018)). The model considers a monopolistic firm producing and instantaneously selling a homogeneous good at a stochastic price. In each instant, the firm optimally decides on how much to produce ("production decision") and whether to install more capacity ("investment decision"). While the original model assumes that investment yields immediately operational capacity (akin to a situation in which existing capacity is acquired), we follow Kydland and Prescott (1982) and Carlson et al. (2010) and allow for a time gap between the investment date and the date the extra capacity becomes operational to model the situation in which capacity is newly built. Following Triantis and Hodder (1990) and He and Pindyck (1992), we further assume that newly-built capacity has extra operating flexibility, implying that it can be reconfigured from producing a firm's main output to some alternative to accommodate customer demands. To model the aging process of newly-built capacity, we however also assume that the extra flexibility vanishes with some probability over time.

Our theoretical work suggests that the extra flexibility of newly-built capacity can explain the investment anomaly. The reason is that, in the model, flexible capacity limits the effect that a drop in the demand for a firm's main output has on its profitability since flexible capacity can be reconfigured to produce other output more desirable to customers. More technically speaking, the value of newly-built flexible capacity is less sensitive to demand than the value of mature inflexible capacity, decreasing its expected return. As the newly-built flexible capacity, however, ages, it eventually turns into mature inflexible capacity, increasing its expected return. Yet, as firms with newly-built capacity lose their extra flexibility on different dates, the investment anomaly only gradually disappears in the aggregate over the course of a couple of years.[3]

The crux of our argument is thus that newly-built capacity tends to be more flexible than mature capacity. To see that this argument is reasonable, we note that a large literature suggests that flexible capacity is the linchpin for corporate survival in uncertain environments (see, e.g., Milgrom and Roberts (1990), Upton (1995), and Trigeorgis and Tsekrekos (2018), etc.). Despite

[3]Consistent with Carlson et al. (2010), we find that allowing for time-to-build has almost no effect on a firm's expected return. While capacity-under-construction has a low sensitivity to changes in demand simply because the profits produced by it are consistently equal to zero over the construction period, it also has a low value for exactly the same reason. Raising time-to-build thus lowers the systematic risk of the capacity-under-construction (decreasing the expected return) but skews firm value away from the low-risk capacity-under-construction and toward the higher-risk capacity-in-place and growth options (increasing the expected return). Taken together, the two effects almost cancel out each other, leaving the firm's expected return close to unchanged.

that, Tolio (2009) warns that flexible capacity is often ill-suited to a firm's unique needs, with it being unable to accommodate those types of flexibility required by the firm to optimally react to changes in its customers' demands. Given that, it appears obvious that firms building capacity from scratch are more capable of ensuring that the extra capacity accommodates the required types of flexibility than firms buying already-existing capacity off-the-shelf.

We finally present empirical evidence supporting that newly-built capacity is more flexible than mature capacity, allowing firms to avoid low demand realizations. To do so, we run panel regressions of a firm's quarterly profit growth on changes in its industry's performance, interacting the change in industry performance with a dummy indicating whether the firm owns newly-built capacity. The regressions suggest that firms with newly-build capacity are less sensitive to their industry's performance than others, especially in poor industry states, revealing that newly-built capacity possesses the characteristics ascribed to flexible capacity in our model.

Our paper contributes to the literature aiming to explain the investment anomaly. Behavioral studies in that literature argue that the anomaly arises because managers often overinvest into value-destroying projects, with investors only gradually seeing through that behavior (e.g., Jensen (1986) and Titman et al. (2004)). In contrast, neoclassical studies claim that the anomaly arises because investing firms convert high-risk growth options into low-risk assets-in-place (e.g., Myers (1977) and Carlson et al. (2006)). Of those explanations, not only does the behavioral explanation have an edge because it can explain why the investment anomaly disappears over time, but also because the neoclassical explanation does not necessarily explain the anomaly, as we show in our work. The reason is that, in the neoclassical explanation, investment is triggered by positive news skewing firm value away from low-risk assets-in-place and toward high-risk growth options, offsetting the effect from the investment-induced conversion of growth options into assets-in-place (see Sagi and Seasholes (2007)). We offer a more successful neoclassical real-options explanation for the anomaly, yielding new testable implications supported by the data.[4]

[4]We do not claim that allowing for flexible capacity is the only channel to ensure that neoclassical real-options models can produce an investment anomaly. Carlson et al. (2004; 2006; 2010), for example, show that limits to

We also add to real options studies modeling the effect of time-to-build and flexible capacity on investment, value, and systematic risk. Majd and Pindyck (1987) and Pindyck (1993) consider a firm optimally timing the progress made on one of its construction projects, imposing an upper bound on progress to ensure a positive time-to-build. In contrast to them, we assume that, once a construction project has started, the firm cannot alter its progress or abandon the project, consistent with Koeva's (2000) results.[5] Fine and Freud (1990) consider a firm in a two-period model with independent multiple-product demands, deriving the investments into flexible and inflexible capacity maximizing expected profitability. Conversely, Triantis and Hodder (1990) determine the value of fixed quantities of flexible and inflexible capacity in a multi-period model with dependent demands. Closest to us, He and Pindyck (1992) determine optimal (incremental) investment policies for flexible capacity and the valuation of such capacity in a continuous-time model. We contribute to this literature by jointly considering time-to-build and flexible capacity and allowing flexibility to depreciate (i.e., disappear) over time.

We structure our paper as follows. Section 2 shows that firms building extra capacity produce a stronger investment anomaly than others. Section 3 introduces a real options model of the firm with time-to-build and flexible capacity consistent with that evidence. Section 4 shows that newly-built capacity is more flexible than mature capacity. Section 5 concludes.

2 The Investment Anomaly and Construction Work

In this section, we offer evidence that firms engaged in construction are responsible for stock-level investment anomalies. We first introduce our analysis variables and data sources, giving more

growth (i.e., assigning an only finite number of growth options to firms) serves the same purpose. Imposing limits to growth, however, has the disadvantage that the real options model predicts that the investment anomaly is stronger for bigger than smaller firms, which is counterfactual (see Fama and French (2008)).

[5] Koeva (2000) reports that about 90% of the construction projects in her sample were completed without delay and that only one single project was ultimately abandoned. She argues that costly penalties imposed on firms for delaying construction work explain her results. In accordance, Lamont (2000) shows that firms' ex-ante investment plans explain about three-quarters of their ex-post variations in investment outlays, suggesting that managers only mildly adjust their original investment plans in response to economic news.

details about the variables in Table A.1 in the appendix. We next show that investing firms yield lower mean future stock returns than others, confirming the existence of the investment anomaly. Most importantly, we finally report that the anomaly only exists among firms engaged in construction over the investment period, but not among zero-construction-work firms.

2.1 Variables and Data Sources

In this section, we introduce our variable definitions and data sources. We measure firm-level investment as the change in gross PPE over the fiscal year ending in calendar year $t-1$ scaled by total assets at the start of that fiscal year, using the measured value from June of calendar year t to May of calendar year $t+1$ (*Investment*). While our investment proxy is identical to that used in Lyandres et al. (2019), it is also highly correlated with other investment proxies, such abnormal scaled capital expenditures (Titman et al. (2004)), capital expenditures growth (Anderson and Garcia-Feijóo (2006) and Xing (2008)), and asset growth variables including assets other than gross PPE (Fama and French (2006; 2008), Cooper et al. (2008), and Lyandres et al. (2008)). In contrast to the capital expenditure variables, our proxy also captures capacity expansions facilitated through asset acquisitions. In contrast to the variables including non-PPE assets, it excludes assets unrelated to the production and sales process (as, e.g., cash and accounts receivables) and assets consumed in that process (as, e.g., input inventories).

We identify firms engaged in construction over the investment period using their PPE-CIP account values (Compustat item: fatc) at the end of that investment period. This account contains all expenses that a firm incurs in the construction of an asset, as, for example, material costs, vendor invoices, and transportation costs, during construction, with the account balance being shifted to a fixed-asset account once construction has finished. Firms with a positive PPE-CIP balance at the end of the investment period thus have outstanding construction work at that time, motivating us to use them as firms engaged in construction. Given PPE-CIP is a subcomponent of gross PPE, our approach to identify firms engaged in construction nicely aligns with how we measure investment since positive *Investment* values could be a result of new PPE-CIP expenses. We also consider the PPE-CIP balance at the end of the investment period scaled by total assets at the start of that period (*Construction*).[6]

We use a standard set of control variables in our empirical work. In the portfolio sorts, we adjust for risk by regressing portfolio returns on the Hou et al. (2015) q-theory factors or the Fama and French (2015) five-factor model factors. In the FM regressions, we control for *MarketBeta*, *MarketSize*, *BookToMarket*, *Momentum*, and *Profitability*. *MarketBeta* is the slope coefficient from a time-series regression of a stock's daily return on the daily market return run over the prior twelve months, requiring there to be at least 200 observations in the estimation period. *MarketSize* is the log of common shares outstanding multiplied by the share price from month $t-1$. *BookToMarket* is the log ratio of the book value of equity from the fiscal year ending in calendar year $t-1$ to the market value of equity from the end of calendar year $t-1$, used from June of calendar year t to May of calendar year $t+1$. *Momentum* is the stock return compounded over the prior twelve months but excluding the most recent month. *Profitability* is sales minus costs of goods sold, selling, general, and administrative expenses, and interest expenses scaled by total assets from the fiscal year ending in calendar year $t-1$, used from June of calendar year t to May of calendar year $t+1$. See Table A.1 in the appendix for more details about the control variables.

We retrieve market data from CRSP, accounting data from Compustat, and data on the q-theory and five-factor model factors from Kenneth French and Lu Zhang. We study the common stocks (share codes: 10 and 11) of firms traded on the NYSE, AMEX, and Nasdaq. To ensure that our sample firms employ at least some physical assets in their production and sales processes, we discard firms from the financial (SIC codes: 6000–6999), utilities (4900–4949), and services (7000–8999) industries. To guard against confounding effects arising from micro stocks, we further

[6] We acknowledge that our approach to identify firms engaged in construction over the investment period is imperfect because construction work driving up *Investment* over that period could have already finished by its end. To mitigate that problem, we have alternatively used firms with a positive PPE-CIP balance at the *start or end* of the investment period as firms engaged in construction, allowing us to also capture construction work started before the investment period but finished within it. Using this alternative identification strategy, we find empirical results almost identical to those reported later.

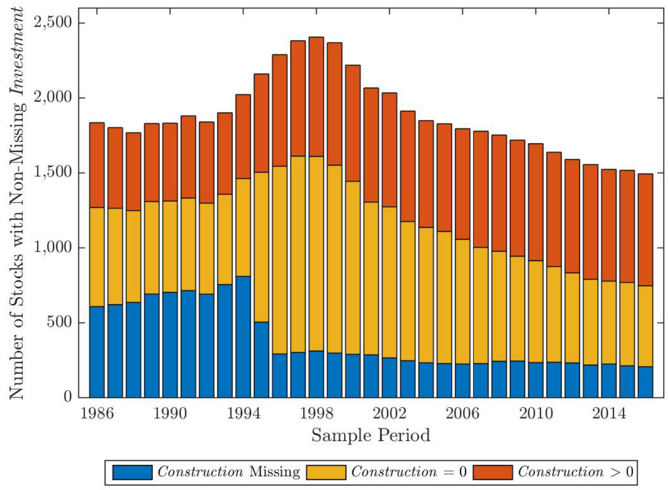

Figure 2: Number of Firms with Positive, Zero, and Missing *Construction* Values In this figure, we plot the number of firms with non-missing *Investment* values and complying with our selection criteria, for each fiscal year over the 1986 to 2016 sample period. The red, yellow, and blue parts of each bar represent the numbers of firms with positive, zero, and missing construction expenses, respectively.

discard firms with a market size below the first quintile in June of calendar year t from the sample period from July of year t to June of year $t+1$. For that same reason, we also discard firms with sales below $25 million in the fiscal year ending in the last calendar year from the period from July of year t to June of year $t+1$. To mitigate backfilling biases, we only consider stocks after they have been included in Compustat for two or more years. In case of stock-exchange delistings, we set a stock's return to the CRSP delisting return. If the CRSP delisting return is missing, we set it to either –30% (delisting codes: 500, 520, 551–573, 574, 580, or 584) or –100% (all other delisting codes; see, e.g., Shumway (1997) and Bali et al. (2017)). With the exception of the stock return, we winsorize all variables at the 0.5th and 99.5th percentiles per month. Spurred by the availability of PPE-CIP data, our sample period is July 1986 to December 2016.

2.2 Descriptive Statistics

In this section, we offer descriptive statistics and correlations on our analysis variables. Figure 2 plots the number of firms that have non-missing *Investment* values and comply with our sample selection criteria over the 1986-2016 period, further decomposing that number into firms with positive (red bars), zero (yellow bars), and missing (blue bars) PPE-CIP values at the end of each investment period. The figure suggests that our sample consists of between 1,500 to 2,500 firms per sample year. Of those, about 40% do not disclose their construction-work expenses until 1994, with that fraction, however, sharply dropping to almost 10% starting from then. Only considering the disclosing firms, about 40% to 60% have unfinished construction work at the end of each investment period. The proportion of unfinished-construction-work firms, however, tends to sharply rise over our sample period. In our last sample year (2016), for example, 747 firms have positive *Construction* values, whereas only 540 firms have zero values.

Table 1 presents descriptive statistics for *Investment*, *Construction*, and a dummy equal to one if *Construction* is positive and else zero (*DummyConstruction*; Panel A). It further presents Pearson rank correlations between those variables and the control variables (Panel B). The descriptive statistics include the mean, standard deviation, skewness, kurtosis, and several percentiles. Panel A suggests that the average sample firm increases its gross PPE by almost six percent of its total assets per year (see the mean of *Investment*). Of the six percent, slightly more than 20% (namely, 1.25%) can be traced to construction work (see the mean of *Construction*). The upshot is that construction work meaningfully contributes to capacity expansions. Notwithstanding, we witness great variations in investment and construction work across firms. While, for example, about 20% of our sample firms disinvest, about 55% raise their gross PPE by less than 10%, leaving only about 25% of firms raising their gross PPE by more than 10%. Conversely, only about 30% of our sample firms engage in construction raising gross PPE by more than 1%.

Panel B shows that construction work has a meaningful effect on gross PPE, with the correlation between *Investment* and *Construction* being 0.23. Neither *Investment* nor *Construction* yield strong correlations with the controls. The exception is the correlation between *Construction* and *MarketSize*, which is a noteworthy 0.15. Thus, while small and large firms display a similar tendency to invest, large firms are more likely to do so through building.

2.3 The Pricing of *Investment*

In this section, we use univariate portfolio sorts to verify that *Investment* produces a significant investment anomaly over our sample period. At the end of June of each year t, we first separate out disinvesting firms (i.e., firms with a negative *Investment* value) and sort them into a disinvestment portfolio. We next sort the remaining firms into portfolios according to the tenth, 30th, 50th, 70th, and 90th percentiles of the *Investment* distribution on that date. We also form a spread portfolio holding long the highest and short the lowest (positive) *Investment* portfolio ("LS90-10"). We value-weight the portfolios and hold them from July of year t to June of year $t + 1$. We adjust the portfolio returns for risk by regressing them on the Hou et al. (2015) q-theory-model or Fama and French (2015) five-factor-model benchmark factors excluding their investment factor and reporting the intercept ("alpha"). We use Gibbons, Ross, and Shanken's (GRS; 1989) F-test to establish whether the benchmark factors correctly price the *Investment* portfolios.

Table 2 presents the results from the univariate portfolio sort, showing the mean excess returns and alphas of the portfolios as well as several portfolio characteristics. The portfolio characteristics are the number of stocks and the cross-sectional means of *Investment* and *Construction*, averaged over our sample period. The table also reports t-statistics for the mean excess return and alphas of the spread portfolio, calculated using Newey and West's (1987) formula with a six-month lag length and in squared parentheses, and the GRS-test p-value in round parentheses.

The table confirms that *Investment* produces a significant negative premium. Ignoring the disinvestment portfolio, mean excess returns decline over the other portfolios, from 10.33% per annum for the lowest *Investment* portfolio to 2.21% for the highest (see column (4)). In line with other recent evidence (e.g., Nyberg and Pöyry (2014)), the decline is however only mild over the initial five portfolios, before becoming large going from the fifth to the sixth portfolio. The initially only mild decline is likely caused by the firms in the first five portfolios only marginally increasing their capacity, as suggested by their mean *Investment* values being below 12% (see column (2)). In contrast, the highest *Investment*-portfolio firms raise their capacity more significantly, as suggested by a mean close to 35%. While the mean *Investment* values increase over the portfolios by construction, the mean *Construction* values increase over them too, implying that sorting firms on *Investment* is similar to sorting them on *Construction* (compare columns (2) and (3)).

Given the trend in mean excess returns over the *Investment* portfolios, the spread portfolio yields a highly significant negative mean return of –8.12% per annum (t-statistic: –3.15). Adjusting for the q-theory or five-factor model benchmark factors does not materially change the magnitude or significance levels of those returns. Finally, the GRS F-test strongly suggests that the benchmark factors are unable to price the portfolios, with p-values never exceeding 0.02.

2.4 The Effect of *Construction* on the Pricing of *Investment*

We next study whether the pricing of *Investment* is conditional on *Construction*. At the end of June of each year t, we thus again first sort firms with a positive *Investment* value into six portfolios according to the tenth, 30th, 50th, 70th, and 90th percentiles of the *Investment* distribution on that date. We next sort the same firms into two portfolios according to whether they have a positive or zero *Construction* value. We finally create the double-sorted portfolios from the intersections of the two sets of univariate portfolios. Within each *Construction* portfolio, we form a spread portfolio long the highest and short the lowest *Investment* portfolios ("LS90-10"). We again value-weight the portfolios and hold them from July of year t to June of year $t + 1$. We risk-adjust the returns of the portfolios using the same methods as in the prior subsection and calculate the GRS F-test separately for the double-sorted portfolios with positive and zero *Construction* values.

Table 3 presents the results from the double-sorted portfolio sort, showing the same statistics as Table 2 but separately for the double-sorted portfolios with positive (left columns) and zero (right columns) *Construction* values. The table suggests that the investment anomaly is attributable to firms engaged in construction activity. While the spread portfolio formed from firms without construction work yields an insignificant mean return of –3.98% per annum (t-statistic: –1.30), the spread portfolio formed from firms with such work yields a highly significant mean return of

–10.36% (t-statistic: –3.09). The spread in these numbers, –6.38%, is mildly significant (t-statistic: –1.71; unreported). Importantly, the difference in the mean spread portfolio return comes mostly from the highest *Investment* portfolio, not the lowest. While the highest *Investment* portfolio has a 4.92% lower mean excess return among positive compared to zero *Construction* value firms, the corresponding number for the lowest *Investment* portfolio is only –1.46% (unreported).

Adjusting for the q-theory or five-factor-model benchmark factors slightly weakens our spread portfolio return results but does not eliminate them. More strikingly, the GRS test suggests that while the benchmark factors can price the no-construction-work *Investment* portfolios (p-values $>$ 0.29), they utterly fail to price those formed from firms with such work (p-values $<$ 0.01).

In Table 4, we use FM regressions to study how construction work conditions the investment anomaly. To do so, we regress the single-stock return over month t on *Investment* and our controls measured until the end of month $t-1$, separately using the full sample (column (1)), the subsample of firms with positive *Construction* values (column (2)), and the subsample of firms with zero *Construction* values (column (3)). Plain numbers are monthly premium estimates in percent, while those in square parentheses are t-statistics obtained from Newey and West's (1987) formula with a six-month lag length. The FM regressions support the conclusions obtained from the double-sorted portfolios. While the zero-construction-work subsample yields an insignificant negative *Investment* premium of –0.53% per month (t-statistic: –1.07), the corresponding number for the positive-construction-work subsample is a highly significant –2.14% (t-statistic: –6.58). The spread in the two numbers is a significant –1.61% (t-statistic: –2.92; see column (4)). The control-variable premiums align with those reported in other studies (see, e.g., Fama and French (2008)).

Figure 3 looks at the economic significance of our results. To do so, we plot the compounded returns from shorting the LS90-10 *Investment* portfolio formed using only firms with non-missing (solid blue line), positive (dashed red line) or zero (dotted yellow line) *Construction* values over our sample period. The figure suggests that shorting the spread portfolio formed from firms with construction work is significantly more profitable than shorting the others. While shorting that

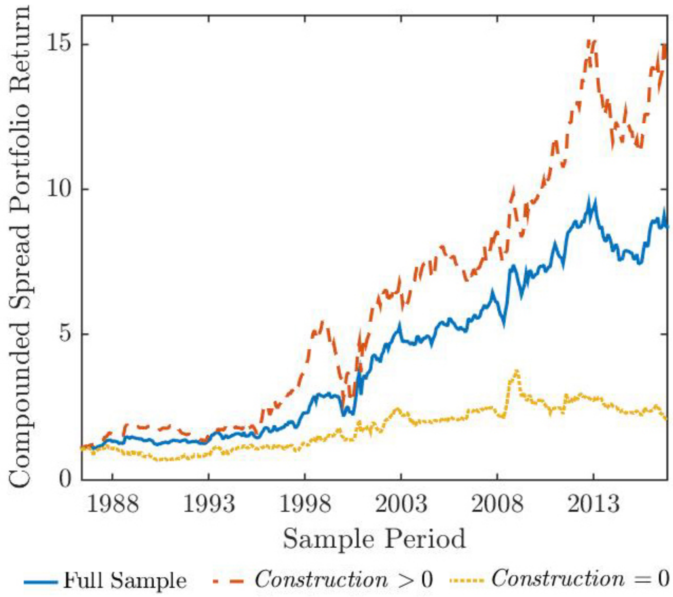

Figure 3: Shorting Investment Spread Portfolios Conditional on Construction Work In this figure, we plot the compounded monthly returns of spread portfolios long the bottom *Investment* decile and short the top decile and formed using firms with non-missing (solid blue line), zero (dashed red line), or positive (dotted yellow line) *Construction* values over our sample period (1986 to 2016).

spread portfolio yields a payoff of about \$15, the corresponding number for the spread portfolio formed from zero *Construction* value firms is an about seven times lower \$2.

Figure 4 finally studies the time-series evolution of the *Investment* premium separately for firms with (Panel A) and without (Panel B) construction work. To that end, we repeat the FM regressions of stock returns on *Investment* and the control variables measured until the end of month t separately run on the two types of firms. This time, however, we lead stock returns by either zero, twelve, 24, 36, or 48 months relative to those in the regressions in Table 4 (first, second, third, fourth, and fifth year after portfolio formation, respectively). The solid line in the figure is the monthly premium estimate. The dotted lines are the 95% confidence bands. The figure suggests that the positive-construction-work subsample yields a strongly significant *Investment* premium over the first two years, but an insignificant premium after that. In contrast, the zero-construction-work subsample yields an insignificant *Investment* premium over the entire five-year period.

Taken together, this section suggests that the investment anomaly is mostly attributable

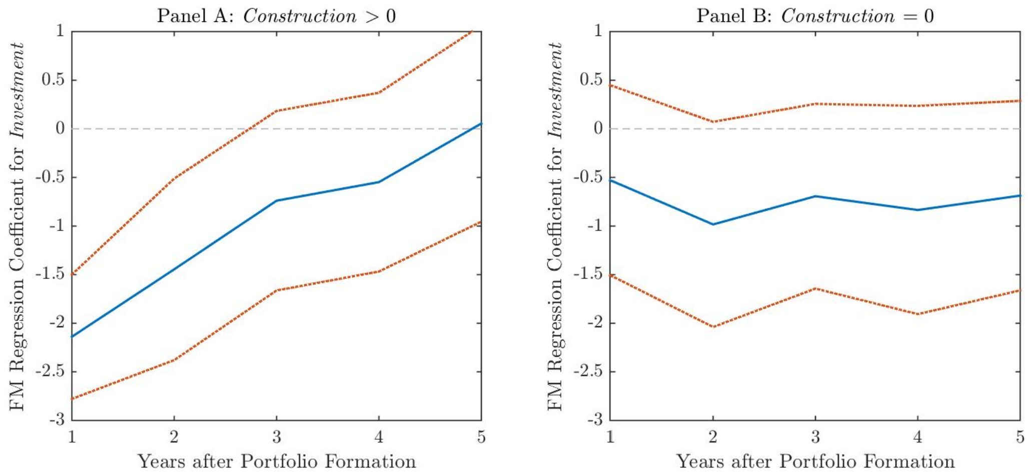

Figure 4: Evolution of the *Investment* Premium Over Time In this figure, we plot the *Investment* premium from FM regressions of single-stock returns over month $t + x + 1$ on *Investment* and controls measured until the end of month t, separately run on firms with a positive (Panel A) and zero (Panel B) *Construction* value at the end of month t. We set x equal to zero, twelve, 24, 36, and 48 (first, second, third, fourth, and fifth year after portfolio formation, respectively). Solid lines are monthly premium estimates in percent, while dotted lines are 95% confidence bands calculated from Newey and West's (1987) formula with a six-month lag length.

to firms building rather than buying extra capacity, with the anomaly, however, continuing to dissipate over time not only in general but also among building firms. In the next section, we develop a real options model of the firm consistent with the evidence established here.

3 A Real Options Model Allowing for Built Capacity

In this section, we study whether real options models of the firm in which firms can buy or build capacity help us understand why the investment anomaly is mostly driven by building firms. We first lay out the intuition behind that model. We next state the model's assumptions and solve it. We finally show that the model is consistent with the empirical evidence in Section 2.

3.1 Intuition

We start with describing the intuition behind the real options model described in this section. The goal of that model is to extend standard models assuming investment yields directly operational capacity and thus considering the case in which already-existing capacity is acquired to the case in which capacity is newly-built. To that end, we need to take a stance on how those cases differ from one another. In line with Kydland and Prescott (1982) and Carlson et al. (2010), we posit that one main difference is that, in contrast to acquiring existing capacity, building capacity often implies that the capacity becomes operational only with some (time-to-build) lag, leading the firm to miss out on profits and thus being a disadvantage to building.

What then, however, is the advantage to building? While the literature is more reluctant to offer a straight answer to that question, an abundance of studies in economics and manufacturing suggest that firms care less about production costs and/or volumes and more about the degree to which capacity can be adapted to changes in their uncertain environments (see, e.g., Milgrom and Roberts (1990), Upton (1995), and Trigeorgis and Tsekrekos (2018)). In his preface, Tolio (2009), for example, writes: "Manufacturing flexibility is usually considered as the main answer for surviving in present markets characterized by short lead times, tight product tolerances, pressure on cost, frequent changes in demand and continuous evolution of the technological requirements of a product." Given that firms can pay more attention to those features they most strongly care about when building capacity from scratch, we thus posit that the main advantage to building is that firms can ensure that newly-built capacity embodies those types of flexibility allowing the firms to react more efficiently to changes in their unique environments. In accordance, our model assumes that, if customers lose interest in a firm's products, the firm can reconfigure newly-built capacity to produce alternatives more desirable to customers, at least for some time.

3.2 Model Assumptions

We next introduce the assumptions of our real options model of the firm. In the model, we study a monopolistic all-equity firm operating in continuous time indexed by $t \in \{0, +\infty\}$. The firm maximizes its net value by deciding in each instant on how much of a homogenous output good to produce ("production decision") and whether to modify its production capacity ("investment decision"). Let the firm's chosen production capacity be $K \in \{0, +\infty\}$, with each capacity unit able to produce one output unit per time unit and incurring a fixed cost f per time unit. Each capacity increment can be costlessly and instantaneously switched on or off to produce an output increment, so that the firm's chosen output quantity is $Q \in \{0, K\}$ per time unit.

The firms sells its output instantaneously at a price P determined by the linear demand function: $\theta - \gamma Q$, where θ denotes stochastic demand and γ the constant elasticity of demand. We assume that stochastic demand θ obeys Geometric Brownian motion (GBM):

$$d\theta = \alpha\theta dt + \sigma\theta dW, \tag{1}$$

where α is the demand drift rate, σ the demand volatility, and W a Brownian motion. Each output unit is produced at a production cost determined by the convex function: $c_1 Q + \frac{1}{2}c_2 Q^2$, where c_1 and c_2 are non-negative parameters. The firm's total profits per time unit, Π, are then:

$$\Pi = PQ - c_1 Q - \frac{1}{2}c_2 Q^2 - fK = (\theta - c_1)Q - (\gamma + \frac{1}{2}c_2)Q^2 - fK. \tag{2}$$

Given that the firm can costlessly and instantaneously choose its output quantity Q only subject to the constraints that output must be non-negative and below capacity K, it will optimally choose its output to be equal to $\max\left(\min\left(\frac{\theta - c_1}{2\gamma + c_2}, K\right), 0\right)$ in each instant.

Having studied the firm's production setup, we now come to its investment policy. In each instant, the firm is able to raise its production capacity at a unit investment cost of k or lower its capacity at a unit disinvestment proceed of d, with $k > d$. As Pindyck (1988) discusses, the firm continues to invest into the incremental production unit until the benefit from doing so, which is the value of the unit, no longer exceed the costs, which are the investment costs plus the loss from sacrificing the option to invest into that unit later. Conversely, the firm continues to disinvest the incremental production option until the benefits from doing so, which are the disinvestment gain plus the value from regaining the option to invest into that unit later, no longer exceed the cost, which is the value of the sold-off unit. Given that investment is partially irreversible (i.e., $k > d$), the firm neither invests nor disinvests capacity in certain regions in the $\{\theta, K\}$ state space.

While the model so far is close to those in prior studies (compare, for example, with Aretz and Pope's (2018) model), we next allow for time-to-build and capacity flexibility to distinguish between situations in which a firm acquires existing capacity off-the-shelf and in which it newly builds capacity tailor-made to serve its unique needs. Following Kydland and Prescott (1982) and Carlson et al. (2010), we allow for time-to-build by adding a non-negative wedge between the date on which the firm invests into capacity and the date on which that capacity becomes operational. Over that "construction period," which is of length $\bar{T}$, the extra capacity is neither able to produce output nor incurs fixed costs. Also, once initiated, the firm cannot abandon (i.e., disinvest) its construction work. Following He and Pindyck (1992), we next allow for capacity flexibility by assuming that newly-built capacity can be instantaneously and costlessly switched to produce two different homogenous output goods. The first is some standard output good produced by the firm's existing capacity, while the second is some alternative output good whose price is only imperfectly correlated with that of the first output good. To keep a quasi-closed-form solution, we make the simplifying assumption that the alternative output good is sold at the constant unit price of $\theta_A > 0$, while being produced at the constant unit production cost of $f > 0$.[7]

Newly-built capacity, however, ages over time, leading it to lose its ability to react flexibly to changes in demand and to turn into capacity only able to produce a firm's main output at some point. To model that process, we assume that the lifetime of the extra flexibility embedded in newly-built capacity follows a Poisson process with intensity λ. The implication is that, conditional on the extra flexibility still being in place at time t, the probability of it being lost over the next instant is λdt (see Chapter 4 in Dixit and Pindyck (1994) for more details).

[7] Our approach to modeling flexible capacity is a special case of the more general approach advocated by He and Pindykck (1992), in which the prices of the alternative goods that the flexible capacity can produce evolve according to correlated GBMs. As He and Pindyck (1992) highlight, their model can in general not be solved in quasi-closed-form. In their numerical example, they thus study flexible capacity only able to produce two alternative goods, which can be sold at log prices that are reciprocals of one another (namely, θ and $1/\theta$.)

3.3 Model Solution

We solve the real options model by valuing the firm's options on its *incremental* output units indexed by $s \in \{0, +\infty\}$. To achieve that, let $V(\theta, s)$ be the value of a mature (i.e., inflexible) option to produce output increment s at a demand of θ, $V^{nb}(\theta, s)$ the value of the equivalent newly-built (i.e., flexible) option, $V^{uc}(\theta, s)$ the value of the equivalent under-construction option, and $G(\theta, \bar{T}, s)$ the value of the option to buy the equivalent under-construction option. Given that the firm always exercises its growth options sequentially (i.e., the lower-s growth options before the higher-s growth options), we can write firm value, W, as:

$$W = \int_0^{K^{ap}} V^{ap}(\theta, s) ds + \int_{K^{ap}}^{K} V^{uc}(\theta, \bar{T}(s), s) ds + \int_K^{\infty} G(\theta, \bar{T}, s) ds, \tag{3}$$

where $V^{ap}(\theta, s) \in \{V(\theta, s), V^{nb}(\theta, s)\}$ is the mature or newly-build installed production option on output increment s depending on whether the option has already lost its extra flexibility, K^{ap} is the firm's installed capacity, and $\bar{T}(s)$ is the remaining construction time for the production option under construction on increment s.[8] Given Equation (4) suggests that the firm is a portfolio of different types of options, it follows from Cox and Rubinstein (1985, p.186) that the instantaneous expected firm return, $E[r_A]$, minus the risk-free rate of return, r, is equal to:

$$\begin{aligned} E[r_A] - r \quad = \quad & \left(\int_0^{K^{ap}} \frac{V^{ap}(\theta, s)}{W} \Omega_{V^{ap}(\theta, s)} ds \right. & (4) \\ + \quad & \int_{K^{ap}}^{K} \frac{V^{uc}(\theta, \bar{T}(s), s)}{W} \Omega_{V^{uc}(\theta, \bar{T}(s), s)} ds & \\ + \quad & \left. \int_K^{\infty} \frac{G(\theta, \bar{T}, s)}{W} \Omega_{G(\theta, \bar{T}, s)} ds \right) \times (\mu - r), & (5) \end{aligned}$$

[8] Since the firm cannot abandon its construction projects, $V^{ap}(\theta, s)$ could, in theory, also be equal to $G(\theta, \bar{T}, s)$, as when increases in demand leading to investment are followed by sharp decreases leading to disinvestment. To accommodate that possibility, we can set $V^{ap}(\theta, s) \in \{V(\theta, s), V^{nb}(\theta, s), G(\theta, \bar{T}, s)\}$. Equation (4) abstracts from that possibility since it is irrelevant for the numerical exercises run in this section.

where $\Omega_{V^{ap}(\theta,s)} \in \{\Omega_{V(\theta,s)}, \Omega_{V^{nb}(\theta,s)}\}$, $\Omega_{V(\theta,s)}$, $\Omega_{V^{nb}(\theta,s)}$ $\Omega_{V^{uc}(\theta,\bar{T}(s),s)}$, and $\Omega_{G(\theta,\bar{T},s)}$ are the elasticities of the mature, newly-built, and under-construction production option and the growth option, respectively, and μ is the instantaneous expected return of a traded-asset portfolio perfectly correlated with demand. Each elasticity is defined as the partial derivative of option value with respect to demand multiplied by the ratio of demand to option value.

Using contingent claims analysis, we show in Appendix A that the value of a mature production option on output increment s given a demand of θ, $V(\theta, s)$, is equal to:

$$V(\theta, s) = \begin{cases} F(\theta, s) + d; & \theta \leq \theta^D \\ b_1\theta^{\beta_1} + b_3\theta^{\beta_2} - \frac{f}{r}; & \theta^D \leq \theta \leq (2\gamma + c_2)K + c_1 \\ b_2\theta^{\beta_2} + \frac{\theta}{\delta} - \frac{(2\gamma+c_2)K+c_1}{r} - \frac{f}{r}; & \theta \geq (2\gamma + c_2)K + c_1, \end{cases} \tag{6}$$

where b_1, b_2, β_1, β_2, and θ^D are parameters defined in the appendix, and $\delta \equiv \mu - \alpha$. The solution can be interpreted as follows. When $\theta \leq \theta^D$, the firm sells the production option, gaining the unit disinvestment proceed d and acquiring the option to repurchase the production option at a unit-investment cost of l in the future. When $\theta^D \leq \theta \leq (2\gamma + c_2)K + c_1$, the firm retains the production option but does not use it to produce output. In that case, the value of the option derives from the possibility that the firm will use it in the future, the possibility that the firm will sell it in the future, and the discounted fixed operating costs. When $\theta \geq (2\gamma + c_2)K + c_1$, the firm uses the option to produce output. In that case, the value of the option derives from perpetually producing output and the possibility that the firm will not use the option in the future. Except for the fixed production costs, the solution mirrors that in Aretz and Pope (2018).

In the same appendix, we further show that the value of a newly-built production option on output increment s given a demand of θ, $V^{nb}(\theta,s)$, is equal to:

$$V^{nb}(\theta,s)=\begin{cases} b_6'\theta^{\beta_1'}+\frac{\theta_A-f}{r+\lambda}+a\theta^{\beta_1}+\frac{\lambda d}{r+\lambda}; & \theta\le\theta^D \\ b_4'\theta^{\beta_1'}+b_5'\theta^{\beta_2'}+\frac{\theta_A}{r+\lambda}+b_1\theta^{\beta_1}+b_3\theta^{\beta_2}-\frac{f}{r}; & \theta^D\le\theta\le(2\gamma+c_2)K+c_1 \\ b_1'\theta^{\beta_1'}+b_3'\theta^{\beta_2'}+b_2\theta^{\beta_2}-\frac{\theta}{\delta+\lambda} & \\ +\frac{\theta_A+(2\gamma+c_2)K+c_1}{r+\lambda}+\frac{\theta}{\delta}-\frac{(2\gamma+c_2)K+c_1+f}{r}; & 0\le\theta-(2\gamma+c_2)K-c_1\le\theta^A \\ b_2'\theta^{\beta_2'}+b_2\theta^{\beta_2}+\frac{\theta}{\delta}-\frac{[(2\gamma+c_2)K+c_1]+f}{r}; & \theta-(2\gamma+c_2)K-c_1\ge\theta_A, \end{cases} \tag{7}$$

where b_1' to b_6', β_1', and β_2' are new parameters defined in the appendix. We can interpret the solution as follows. When $\theta\le\theta^D$, the firm uses the newly-built capacity to produce the alternative output good, but immediately sells the capacity upon losing the ability to do so. In that case, the value of the option derives from producing the alternative output good, switching to producing the standard output good, and selling off the capacity upon losing the extra flexibility. When $\theta^D\le\theta\le(2\gamma+c_2)K+c_1$, the firm also produces the alternative output good, but keeps the option idle upon losing the ability to do so. In that case, the option's value derives from producing the alternative output good, switching, and owning an idle production option upon losing the extra flexibility. The situation is similar when $\theta_A\ge\theta-(2\gamma+c_2)K-c_1$ except that the firm now uses the capacity to produce the standard output good upon losing the extra flexibility. When $\theta-(2\gamma+c_2)K-c_1\ge\theta_A$, the firm currently produces the standard output independent of whether the capacity is flexible enough to produce either the standard or alternative output good.[9]

The same appendix also show that the value of an under-construction production option on increment s given a demand of θ and a remaining construction time of $\bar{T}(s)$, $V^{uc}(\theta,\bar{T}(s),s)$, is:

$$V^{uc}(\theta,\bar{T}(s),s)=V_1^{uc}(\theta,\bar{T}(s),s)+V_2^{uc}(\theta,\bar{T}(s),s)+V_3^{uc}(\theta,\bar{T}(s),s)+V_4^{uc}(\theta,\bar{T}(s),s), \tag{8}$$

[9] The solution for $V^{nb}(\theta,s)$ assumes that newly-built capacity is so valuable that it is never disinvested. Allowing newly-built capacity to be disinvested is easy to implement but significantly complicates the solution without changing the economic intuition behind our model. To be more specific, allowing newly-built capacity to be disinvested leads its value to become even higher and its systematic risk to be even lower, only strengthening our conclusions.

where $V_1^{uc}(\theta, \bar{T}(s), s)$ to $V_4^{uc}(\theta, \bar{T}(s), s)$ are defined in the appendix. When capacity is under construction, it is uncertain in which region in Equation (7) demand will be once construction work is finished. Thus, each summand in Equation (8) represents the value of a binary option, paying off the value of a newly-build production option if demand is in a specific region and else zero. The $V_1^{uc}(\theta, \bar{T}(s), s)$ summand, for example, is the present value of being awarded newly-built capacity producing the standard output good and continuing to do so if its extra flexibility is lost (i.e., the value of newly-built capacity under the assumption that $\theta - (2\gamma + c_2)K - c_1 \geq \theta_A$).

The appendix finally shows that the value of a growth option enabling the firm to pay a unit investment cost of k to obtain a production option under construction given a demand of θ and an overall construction time of $\bar{T}$, $G(\theta, \bar{T}, s)$, is equal to:

$$G(\theta, \bar{T}, s) = \begin{cases} e\theta^{\beta_1}; & \theta \leq \theta^* \\ V^{uc}(\theta, \bar{T}, s) - k; & \theta \geq \theta^*, \end{cases} \tag{9}$$

where e and θ^* are defined in the Appendix. We can interpret θ^* as the demand threshold at or above which the firm exercises the growth option, pays the unit investment cost k, and obtains the under-construction production option on output increment s worth $V^{uc}(\theta, \bar{T}, s)$.

While perhaps not immediately obvious, the model in this section nests more standard real options models of the firm assuming investment yields immediately operational but inflexible extra capacity (i.e., models focusing on the situation in which extra capacity is bought, and not built). Specifically, we can collapse the model in this section to a more standard model by setting $\bar{T}$, the initial construction time, and θ_A, the flexibility benefit, equal to zero.

3.4 Model Conclusions

We finally confirm that our real options model of the firm allowing for time-to-build and capacity flexibility is able to explain why the investment anomaly is attributable to firms building rather than buying new productive capacity. To do so, we consider a firm owning an optimal amount of capacity given demand, K^*. We next induce a positive shock to demand, triggering investment in the form of the firm either acquiring or building new capacity. In both cases, the pre-shock demand value is 1.50 and the post-shock value is 2.50. Moreover, the annualized drift rate, α, and volatility, σ, of demand are 0.06 and 0.20, respectively. The demand elasticity, γ, is 0.25. The variable cost parameters, c_1 and c_2, are 0.20 and 0.00, respectively, while the fixed cost parameter, f, is 0.05. The expected return of the demand mimicking portfolio, μ, is 0.16, while the risk-free rate of return, r, is 0.04, both per annum. The disinvestment proceeds, d, are zero.

When the firm builds new capacity, the initial construction time, $\bar{T}$, is 1.5, in line with Koeva's (2000) evidence that it takes an average of about 18 months to build a new factory. The extra flexibility of newly-built capacity allows the firm to sell the alternative output good at a profit, θ_A, of 0.75, but disappears with a probability, λ, of 0.10 per annum. We finally set the unit cost of acquiring new capacity, k, to one, but the unit cost of building new capacity to 5.05, consistent with evidence that existing property sells at a significant discount compared to newly-built property and ensuring that the initial optimal capacity, K^*, is identical under buying or building.

Table 5 reports the effect of the positive demand shock on the firm's expected excess return, $E[r_A] - r$, assuming that the firm either acquires (Panel A) or builds (Panel B) new capacity in response to the shock. In addition to the expected excess return, the table also reports installed and optimal capacity (K and K^*, respectively), the fractions of firm value attributable to the production $((\int_0^{K^{ap}} V^{ap}(\theta, s)ds + \int_{K^{ap}}^{K} V^{uc}(\theta, \bar{T}(s), s)ds)/W)$ and growth $(\int_K^{\infty} G(\theta, \bar{T}, s)ds/W)$ options, and the (scaled) systematic risk of the production $(\int_0^{K^{ap}} \frac{V^{ap}(\theta,s)}{W}\Omega_{V^{ap}(\theta,s)}ds + \int_{K^{ap}}^{K} \frac{V^{uc}(\theta,\bar{T}(s),s)}{W}$ $\Omega_{V^{uc}(\theta,\bar{T}(s),s)}ds)$ and growth $(\int_K^{\infty} \frac{G(\theta,\bar{T},s)}{W}\Omega_{G(\theta,\bar{T},s)}ds)$ options. The expected excess firm return is a value-weighted average of the systematic risk of the two types of options multiplied by the expected excess return of the demand mimicking portfolio, $\mu - r$. The rows in each panel give the above statistics before the shock occurs, after the shock has occurred but before the firm has adjusted its capacity, and after the shock has occurred and after the firm has adjusted its capacity. In case the firm builds new capacity, we separately consider the final set of statistics at the start of the construction period and once the newly-built capacity has lost its extra flexibility.

Starting with the case in which the firm acquires new capacity, Panel A of Table 5 suggests that both the pre-shock installed and optimal capacity of the firm is equal to 1.44 (see the row titled "pre-shock"). The positive demand shock raises optimal capacity to 3.10 and, in the absence of capacity adjustments, decreases the systematic risk of the production and growth options and skews firm value away from the lower-risk production options and toward the higher-risk growth options (see "post-shock, old K").[10] Since the negative effect on the expected excess return induced through systematic risk, however, almost cancels out with the positive effect induced through the firm value weights, the expected excess return hardly changes. The firm eventually reacts to the shock by raising its installed capacity upward to its optimal capacity, reversing the above effects. The capacity adjustment increases again the systematic risk of the two types of options while skewing firm value away from the higher-risk options and toward the lower-risk options (see "post-shock, new K"). Yet, for the same reasons as before, the expected excess return hardly reacts.

Turning to the case in which the firm builds new capacity, Panel B confirms that, under our assumptions for the investment costs k, the buying and building firms have an identical pre-shock optimal capacity (see "pre-shock"). The positive demand shock now raises optimal capacity to 3.38 and, in the absence of capacity adjustments, again has a negative effect on the expected excess return through lowering the systematic risk of the two types of options and a positive effect through skewing firm value toward the higher-risk options (see "post-shock, old K"). As before, however, the two effects virtually cancel out other. The firm eventually reacts to the shock by starting to build new capacity, raising installed capacity upward to optimal capacity. Doing so, the expected excess return markedly drops, from 26% to 19% at the start of the construction period (see "post-shock, new K^C"). The reason is that, compared to the buying case, the construction (and later ownership) of newly-built capacity leads the systematic risk of the production options to fall further, from

[10]The negative effect on systematic risk arises because the positive demand shock pushes both the production and growth options further into-the-money. The skewing of firm value away from production and toward growth options is a direct consequence of the growth options having a higher elasticity than the production options.

1.52 before the capacity adjustment to 1.41 after, simply because newly-built capacity has a low systematic risk due to its extra flexibility. Once the extra flexibility of newly-built capacity has, however, vanished, the expected excess return shoots back up again to 25%, coming close to the estimate produced by the standard model in Panel A (see "post-shock, new K").

Overall, this section develops a new real options model of the firm with time-to-build and flexible capacity allowing us to model both the situations in which the firm acquires and in which it builds new capacity. The model is able to explain both why the investment anomaly is driven by firms building rather than buying new capacity but also why it reverses over time, as documented in Section 2. The main assumption allowing the model to do so is that newly-built capacity is more flexible than mature capacity, consistent with a large literature in economics and manufacturing. In the next section, we offer additional empirical evidence supporting that assumption.

4 Construction Work and Operating Flexibility

Our theoretical work in the prior section indicates that a greater operating flexibility of newly-built capacity compared to mature capacity may possibly explain why the investment anomaly is driven by firms building rather than buying new capacity in the data. While we believe that the assumption that newly-built capacity is more flexible than mature capacity is reasonable, we now also offer empirical evidence supporting that assumption. To do so, we start by introducing our methodology, variable definitions, and data sources, offering more details about the variables in Table A.2 of the appendix. We then present our supportive evidence obtained from panel regressions.

4.1 Methodology, Variables, and Data Sources

Our real options model in Section 3 assumes that flexible capacity enables a firm to dynamically react to changes in customer demands, ensuring the firm always offers those products to customers that they desire. As a result, flexible capacity keeps demand for a firm's products high, effectively truncating the future demand distribution from below. The upshot is that when demand for an industry's generic output is high, the firms with both flexible and inflexible capacity in that industry should perform well since both benefit from the high demand. Conversely, however, when demand is low, the firms with flexible capacity should perform less poorly than their competitors since they are better able to adapt their products to customer demands. In our model, flexible capacity thus decreases a firm's sensitivity to its industry's performance, especially in bad states.

We employ panel regressions to study whether firms with newly-built capacity are less sensitive to their industry's performance than other firms, testing whether newly-built capacity inherits the above characteristics of flexible capacity and can thus (presumably) be seen as flexible. To achieve that goal, we estimate the following regression model on quarterly firm-level data:

$$\begin{aligned} ProfitGrowth_{i,k,t} &= \alpha_i + \beta IndustryPriceGrowth_{k,t} + \gamma NewlyBuiltCapacity_{i,k,t} \\ &+ \delta(IndustryPriceGrowth_{k,t} \times NewlyBuiltCapacity_{i,k,t}) \qquad (10) \\ &+ \eta' Controls_{i,k,t} + \epsilon_{i,k,t}, \end{aligned}$$

where *ProfitGrowth* is the scaled change in the gross profits of firm i in industry k from quarter $t-1$ to t, *IndustryPriceGrowth* is the change in the average price at which the firms in industry k sell their output over the same period, *NewlyBuiltCapacity* is a dummy equal to one if firm i owns newly-built capacity in quarter t, and *Controls* is a vector of control variables. α_i is a firm fixed effect, β, γ, and δ are parameters, η is a vector of parameters, and ϵ is the residual.

We calculate *ProfitGrowth* as the change in quarterly sales (Compustat items: saleq) minus quarterly costs of goods sold (cogsq) from calendar quarter $t-1$ to t scaled by total assets at end of quarter $t-1$. To measure *IndustryPriceGrowth*, we start with Chang and Hwang's (2015) NAICS industry classification scheme, aggregating firm-level sales data (saleq) to calculate each industry's sales growth from calendar quarter $t-1$ to t.[11] To avoid spurious regression results, we however

[11] While there are 74 industries in Chang and Hwang's (2015) classification scheme, we only study those with more than ten firms in every quarter, leaving us with the 32 industries shown Table A.3 of the appendix.

calculate industry sales growth separately for each firm in an industry, in each case excluding the firm under consideration. We next obtain data on quarterly output quantity growth for the industries over the same period. Plugging the sales growth (*IndustrySalesGrowth*) and output quantity growth (*IndustryQuantityGrowth*) of industry k from calendar quarter $t-1$ to t into:

$$IndustrySalesGrowth_{k,t} = IndustryPriceGrowth_{k,t} \times IndustryQuantityGrowth_{k,t}, \qquad (11)$$

we back out *IndustryPriceGrowth*, the growth in the average price at which the firms in industry k sell their products over that period.[12] In calculating either *ProfitGrowth* or *IndustryPriceGrowth*, we assume that, when a firm's fiscal quarters do not correspond to calendar quarters, quarterly sales and quarterly costs of goods sold are evenly distributed over the three months of a fiscal quarter and total assets are the same at the end of each month in the quarter.

Since our real options model assumes that the extra flexibility of newly-built capacity gradually disappears over time, we set the *NewlyBuiltCapacity* dummy equal to one if a firm had a positive *Construction* value in at least one year over the prior five. If this condition is not fulfilled, we assume the firm owns only mature capacity, setting *NewlyBuiltCapacity* equal to zero.

In some of our estimations, we use the following controls. *LagProfitGrowth* is one-quarter lagged *ProfitGrowth*. *QuarterlyReturn* is the contemporaneous quarterly stock return. *Momentum* is the compounded one-year return measured until the end of the prior quarter. *MarketSize* is the log of market capitalization at the end of the prior quarter. *BookToMarket* is the log ratio of the book value of equity from the fiscal year end preceding but being closest to the end of the prior quarter to market capitalization at the end of the prior quarter.

We estimate regression (10) on those firms also used in our portfolio sorts and FM regressions

[12] The sales of firm i in quarter t, *Sales*, are equal to its output quantity, *Quantity*, multiplied by its output price, *Price*, in the quarter. Summing that identity over all N firms in industry k, we obtain: $\sum_{i=1}^{N} Sales_{i,k,t} = \sum_{i=1}^{N}(Quantity_{i,k,t} \times Price_{i,k,t})$. Multiplying and dividing the right-hand side by the sum over all firms' quantities in industry k, we obtain: $\sum_{i=1}^{N} Sales_{i,k,t} = \sum_{i=1}^{N} Quantity_{i,k,t} \times \left(\sum_{i=1}^{N} \frac{Quantity_{i,k,t}}{\sum_{i=1}^{N} Quantity_{i,k,t}} \times Price_{i,k,t}\right)$. Dividing the last equality for quarter t by the equality for quarter $t-1$, we finally obtain Equation (11).

in Section 2. More specifically, we include a firm-quarter observation in regression (10) if the firm was included in the portfolio sorts or FM regressions over the prior five years. A firm's data for the fourth quarter of 1990 is, for example, included in the regression if the firm ended up in one of the *Investment* portfolios formed between June 1986 and June 1990.

We obtain market data from CRSP, annual and quarterly accounting data from Compustat, and data on the NAICS industry output quantities from the Federal Reserve's G.17 Industrial Production and Capacity Utilization database. We winsorize each variable (with the exception of the interaction) at the first and last percentiles computed per calendar quarter.

4.2 The Industry Sensitivity of Newly-Built Capacity

Table 6 reports the results from estimating regression (10) using the full sample (columns (1) to (2)) or subsamples for which each industry's compounded *IndustryPriceGrowth* over the prior two years is either above ((3) and (4)) or below ((5) and (6)) the full-sample median. Plain numbers are parameter estimates; the numbers in square parentheses are t-statistics calculated from White (1980) standard errors. While the regressions in columns (1), (3), and (5) only include *IndustryPriceGrowth*, *NewlyBuiltCapacity*, and their interaction, those in columns (2), (4), and (6) also include the controls *LagProfitGrowth*, *QuarterlyReturn*, *Momentum*, *MarketSize*, and *BookToMarket*.

Starting with the full-sample regressions in columns (1) and (2), the table suggests that changes in firms' profits are highly sensitive to changes in their industries' performances. The coefficients on *IndustryPriceGrowth* in those columns are, for example, both equal to 0.004, with t-statistics lying above 6.75. Interestingly, however, there is no strong evidence that newly-built capacity induces firms' profits to grow at a different pace, as can be seen from the insignificant coefficients on *NewlyBuiltCapacity* in the presence of the control variables. Instead, newly-built capacity makes a firm's profit growth less sensitive to changes in its industry's performance, with the coefficients on the interaction between *IndustryPriceGrowth* and *NewlyBuiltCapacity* equal to –0.003 (t-statistic: –3.16) and –0.002 (t-statistic: –3.32) in columns (1) and (2), respectively.

Going a step further, the regressions in columns (3) to (6) explore whether the lower sensitivity of newly-built capacity to industry performance materializes mostly in states when the industry performs poorly, as predicted by our real options model assuming that flexible capacity truncates the future demand distribution from below. The regressions strongly support that prediction. To see that, note that the coefficients on the interaction between *IndustryPriceGrowth* and *NewlyBuiltCapacity* are insignificant when past *IndustryPriceGrowth* is above the full-sample median (see columns (3) and (4)), but significantly negative when it is below the median (see columns (5) and (6)). In words, while firms with newly-built capacity are similarly sensitive to their industry's performance as their industry peers in good states, they are significantly less sensitive in bad states.

The effects of the controls align with intuition. The *LagProfitGrowth* coefficient is negative and significant, suggesting important seasonality in firms' profits. Consistent with stock returns reflecting profitability shocks, the *QuarterlyReturn* coefficient is also positive and significant. In line with Novy-Marx's (2013) evidence, *Momentum* is significantly positively related to *ProfitGrowth*, while *MarketSize* and *BookToMarket* are significantly negatively related to it.

Taken together, this section offers evidence supporting one of the main assumptions of the real options model developed in Section 3. In particular, it suggests that newly-built capacity inherits the main characteristic ascribed to flexible capacity in the real options model, namely, that flexible capacity truncates the future demand distribution from below.

5 Conclusion

In this paper, we offer empirical evidence that the investment anomaly is driven by firms building rather than buying new productive capacity. We rationalize this finding using a real options model of the firm allowing for time-to-build and flexible capacity to describe both situations in which firms buy and build new capacity. In the model, newly-built capacity enables a firm to dynamically react to changes in its customer demand, allowing the firm to offer customers those products that they desire and truncating the demand distribution from below. Given this “insurance property” of newly-built capacity, firms building new capacity experience declines in their expected returns, which however reverse as the newly-built capacity ages and loses its extra flexibility. Further empirical work supports the idea that newly-built capacity is more flexible than mature capacity.

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Table 1
Descriptive Statistics
The table presents descriptive statistics for *Investment*, *Construction*, as well as *DummyConstruction* (Panel A) and Pearson correlations between those variables and our controls (Panel B). The descriptive statistics include the mean, the standard deviation, skewness, kurtosis, and several percentiles. We calculate the descriptive statistics and correlations by month and then average over time. With the exception of skewness and kurtosis, the statistics for *Investment*, *Construction*, and *DummyConstruction* are in percentage terms. See Table AI in Appendix A for variable definitions.

	Investment	*Construction*	*Dummy Construction*
	(1)	(2)	(3)
Panel A: Descriptive Statistics			
Mean	5.98	1.25	0.47
Standard Deviation	10.96	2.51	0.50
Skewness	2.02	3.61	0.12
Kurtosis	14.29	20.19	1.07
Percentile 1	−21.24	0.00	0.00
Percentile 5	−5.33	0.00	0.00
First Quartile	1.33	0.00	0.00
Median	3.98	0.06	0.30
Third Quartile	8.37	1.55	1.00
Percentile 95	23.76	5.72	1.00
Percentile 99	54.31	13.09	1.00
Panel B: Pearson Correlations			
Construction	0.23		
DummyConstruction	0.08	0.53	
MarketBeta	0.05	0.05	0.01
MarketSize	0.04	0.15	0.16
BookToMarket	−0.11	−0.04	0.00
Momentum	−0.06	−0.02	0.01
Profitability	0.07	0.04	0.05

Table 2
Univariate Investment Portfolios

The table presents the mean returns and alphas of portfolios univariately sorted on *Investment*. At the end of June of each calendar year t, we first sort stocks with a negative *Investment* value into a disinvestment portfolio. We then sort the remainder into six further portfolios according to the tenth, 30th, 50th, 70th, and 90th percentiles of the *Investment* distribution in that month. We value-weight the portfolios and hold them from the start of July of year t to the end of June of year $t+1$. We also form a spread portfolio long the highest and short the lowest (positive) investment portfolio ("LS90-10"). The first three plain numbers are the mean number of stocks and the time-series means of the value-weighted cross-sectional means of *Investment* and *Construction* per portfolio. The following three plain numbers are the mean excess returns and alphas generated by the q-theory and five-factor (FF5) model (excluding their investment factors), annualized and in percent. The numbers in square brackets are t-statistics calculated using Newey and West's (1987) formula with a six-month lag length. The table also shows the F-statistic from the Gibbons et al. (GRS; 1989) test, with the p-value in round parentheses. See Table AI in Appendix A for variable definitions.

	Number Stocks	*Investment*	*Construction*	Mean Excess Return	q-Theory Alpha	FF5 Alpha
	(1)	(2)	(3)	(4)	(5)	(6)
Disinvestment	239	−4.72	1.30	7.83	0.57	−0.07
00-10	125	0.59	1.11	10.33	2.08	0.90
10-30	251	2.04	1.31	8.02	0.90	0.31
30-50	251	3.84	1.67	8.22	−0.37	−0.31
50-70	251	6.37	2.10	8.34	0.66	1.52
70-90	251	11.64	2.63	8.79	1.19	2.47
90-100	125	32.08	3.45	2.21	−5.50	−5.73
LS90-10				−8.12	−7.59	−6.62
t-statistic				[−3.15]	[−3.23]	[−3.30]
GRS					2.50	3.05
p-value					(0.02)	(0.01)

Table 3
Double-Sorted Portfolios on Investment and Construction

The table presents the mean returns and alphas of portfolios double-sorted on *Investment* and *DummyConstruction*. At the end of June of each calendar year t, we first exclude stocks with a negative *Investment* value. We then sort the remainder into six portfolios according to the tenth, 30th, 50th, 70th, and 90th percentiles of the *Investment* distribution in that month. We independently sort them into two portfolios according to whether *DummyConstruction* is zero or one in that month. The intersection of the two sets gives us the double-sorted portfolios. We value-weight the portfolios and hold them from the start of July of year t to the end of June of year $t+1$. Within each *Construction* portfolio, we also form a spread portfolio long the highest and short the lowest (positive) investment portfolio ("LS90-10"). The plain numbers in the upper rows are the mean number of stocks and the time-series means of the value-weighted cross-sectional means of *Investment* and *Construction* per portfolio. The plain numbers in the lower rows are the mean excess returns and alphas generated by the q-theory and five-factor (FF5) model (excluding their investment factors), annualized and in percent. The numbers in square brackets are t-statistics calculated using Newey and West's (1987) formula with a six-month lag length. The table also shows the F-statistic from the Gibbons et al. (GRS; 1989) test, with the p-value in round parentheses. See Table AI in Appendix A for variable definitions.

	$DummyConstruction = 1$			$DummyConstruction = 0$		
	Number Stocks	*Investment*	*Construction*	Number Stocks	*Investment*	*Construction*
00-10	42	0.58	2.05	83	0.59	0.00
10-30	101	2.07	2.27	150	2.00	0.00
30-50	113	3.85	2.84	138	3.83	0.00
50-70	126	6.35	3.57	125	6.42	0.00
70-90	134	11.76	4.50	116	11.57	0.00
90-100	72	32.48	5.55	53	31.63	0.00
	Mean Excess Return	q-Theory Alpha	FF5 Alpha	Mean Excess Return	q-Theory Alpha	FF5 Alpha
00-10	11.02	2.69	1.12	9.56	1.53	0.43
10-30	8.60	1.12	0.36	8.01	1.10	0.81
30-50	8.30	−0.20	−0.44	8.25	−0.84	−0.60
50-70	8.13	0.32	0.90	9.24	1.99	2.98
70-90	10.09	2.95	3.87	7.23	−0.94	0.71
90-100	0.66	−6.71	−6.02	5.58	−3.41	−5.17
LS90-10	−10.36	−9.40	−7.14	−3.98	−4.93	−5.61
t-statistic	[−3.09]	[−3.03]	[−2.59]	[−1.30]	[−1.64]	[−1.99]
GRS		3.03	2.94		0.77	1.24
p-value		(0.01)	(0.01)		(0.59)	(0.29)

Table 4
Fama-MacBeth Regressions of Stock Returns on Investment
The table present the results from Fama-MacBeth (1973) regressions of stock returns over month t on pricing variables measured until the end of month $t-1$. We run the regressions separately for the full sample, the subsample of stocks with a positive *DummyConstruction* value, and the subsample of stocks with a zero value (columns (1) to (3), respectively). We also show differences in estimates across the two subsamples (column (4)). The plain numbers are premia, by month and in percent. The numbers in squares are t-statistics calculated using Newey and West's (1987) formula with a six-month lag length. See Table AI in Appendix A for variable definitions.

	Full	*DummyConstruction*		
	Sample	One	Zero	Difference
	(1)	(2)	(3)	(2)–(3)
Investment	−1.61	−2.14	−0.53	−1.61
	[−5.44]	[−6.58]	[−1.07]	[−2.92]
MarketBeta	0.04	0.01	0.06	−0.04
	[0.17]	[0.05]	[0.26]	[−0.37]
MarketSize	−0.05	−0.07	−0.04	−0.03
	[−1.14]	[−1.48]	[−0.86]	[−0.88]
BookToMarket	0.19	0.08	0.24	−0.17
	[2.08]	[0.71]	[2.78]	[−1.96]
Momentum	0.77	0.79	0.76	0.02
	[3.66]	[3.28]	[3.75]	[0.15]
Profitability	0.61	0.47	0.56	−0.09
	[3.23]	[2.27]	[2.44]	[−0.46]
Constant	1.06	1.15	0.98	0.18
	[2.42]	[2.69]	[2.14]	[0.83]

Table 5
Expected Returns and Investment

The table presents the effect of investment on a firm's expected return in a version of Pindyck's (1988) real options model that allows for disinvestment and fixed operating costs. Panel A reports the results for the benchmark model. Panel B reports the results for the model featuring time-to-build and flexible capacity. The columns show the installed and optimal capacity of the firm, the value weights ("weight") and elasticities ("risk") of its assets-in-place and growth options, and its expected return separately for three states. The first state is a lower demand value state in which installed capacity equals optimal capacity ("pre-shock"). The second is a higher demand value state in which the firm has not yet decided to raise its installed capacity to its new optimal capacity ("post-shock, old K"). For Panel A, the third is a higher demand value state in which installed capacity again equals optimal capacity ("post-shock, new K"). For Panel B, the third is a higher demand value state in which the firm has begun construction work to raise its installed capacity to the optimal level by adding flexible capacity ("post-shock, new K^C"). The fourth is a higher demand value state in which all installed capacity is mature and equals optimal capacity ("post-shock, new K"). The pre-shock demand value is 1.50 and the post-shock demand value is 2.50. The base case parameters are: The drift rate, α, and volatility, σ, of demand are 0.06 and 0.20 per annum, respectively. The elasticity of demand, γ, is 0.25. The cost parameters, c_1 and c_2, are 0.20 and zero, respectively. The investment cost, k, is 1 for Panel A and 5.05 for Panel B. These values make the initial optimal capacity identical in the two scenarios. The expected return of the demand mimicking portfolio, μ, is 0.16 per annum. The risk-free rate of return, r_f, is 0.04 per annum. The operating cost, f, is 0.05, while the proceeds from disinvestment, d, is zero. Time-to-build, $\bar{T}$, is 1.5, the selling price of the alternative good, θ_A, is 0.75, and the probability that the new capacity's ability to produce the alternative output will disappear, λ is 0.10.

	Inst. Capacity	Opt. Capacity	Assets-in-Place		Growth Options		Expected
	K	K^*	Weight	Risk	Weight	Risk	Return
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Panel A: Benchmark Model							
Pre-Shock	1.44	1.44	0.82	1.92	0.18	4.45	0.28
Post-Shock, Old K	1.44	3.10	0.59	1.52	0.41	3.40	0.27
Post-Shock, New K	3.10	3.10	0.87	1.86	0.13	4.45	0.26
Panel B: Model with Time-to-Build and Flexibility							
Pre-Shock	1.44	1.44	0.90	1.92	0.11	4.45	0.26
Post-Shock, Old K	1.44	3.38	0.71	1.52	0.29	3.65	0.26
Post-Shock, New K^C	3.38	3.38	0.93	1.41	0.07	4.45	0.19
Post-Shock, New K	3.38	3.38	0.93	1.91	0.07	4.45	0.25

Table 6
Panel Regressions of Profit Growth on Industry Conditions

The table present the results from panel regressions of a firm's profit growth over calendar quarter t on a set of variables measured either over the same or until the end of the previous quarter. We run the regression separately for the full sample (columns (1) and (2)), the subsample of firm-quarter observations with a high industry price growth over the prior two years (columns (3) and (4)), and the subsample of those with a low industry price growth over the same period (columns (5) and (6)). We include firm fixed effects in all regressions. The plain numbers are coefficient estimates, while the numbers in square brackets are t-statistics calculated using White (1980) standard errors. See Tables AII and AIII in Appendix A for variable and industry definitions, respectively.

	Full Sample		Past *Industry PriceGrowth* Above Median		Past *Industry PriceGrowth* Below Median	
	(1)	(2)	(3)	(4)	(5)	(6)
IndustryPriceGrowth	0.004	0.004	0.003	0.004	0.006	0.005
	[6.75]	[7.21]	[3.39]	[4.06]	[6.63]	[6.45]
NewlyBuiltCapacity	−0.001	−0.000	−0.001	−0.001	−0.001	−0.000
	[−2.72]	[−0.81]	[−1.68]	[−0.77]	[−1.77]	[−0.23]
IndustryPriceGrowth	−0.003	−0.002	−0.001	−0.002	−0.004	−0.003
× *NewlyBuiltCapacity*	[−3.16]	[−3.32]	[−0.69]	[−1.51]	[−3.85]	[−3.29]
LagProfitGrowth		−0.202		−0.189		−0.226
		[−30.13]		[−19.33]		[−23.72]
QuarterlyReturn		0.009		0.010		0.009
		[19.70]		[14.76]		[11.98]
Momentum		0.002		0.002		0.002
		[9.29]		[6.69]		[6.21]
MarketSize		−0.002		−0.002		−0.002
		[−13.03]		[−8.48]		[−8.86]
BookToMarket		−0.003		−0.004		−0.003
		[−14.07]		[−9.89]		[−8.82]
Constant	0.004	0.011	0.004	0.011	0.004	0.011
	[12.65]	[13.21]	[8.60]	[8.65]	[8.06]	[8.93]

Appendix A. Variable and Industry Definitions

Table AI
Analysis Variables Used In Our Asset Pricing Tests
The table presents the definitions of the variables used in the descriptive statistics, portfolio sorts, and Fama-MacBeth (FM; 1973) regressions in Tables 1 to 4. We give the variable mnemonics assigned by the data providers (CRSP and Compustat) in parentheses. We use the values of the variables calculated as described from July of year t to June of year $t+1$. The exceptions are the values of *MarketBeta*, *MarketSize*, and *Momentum*, which we use in month t alone.

Variable Name	Variable Definition
Investment	The change in gross property, plant, and equipment (ppegt) from the fiscal year ending in calendar year $t-2$ to the fiscal year ending in calendar year $t-1$ scaled by total assets (at) from the fiscal year ending in calendar year $t-2$.
Construction	The ratio of gross property, plant, and equipment construction-in-progress (fatc) from the fiscal year ending in calendar year $t-1$ to total assets (at) from the fiscal year ending in calendar year $t-2$.
DummyConstruction	A dummy variable equal to one if *Construction* is positive, else zero.
MarketBeta	The slope coefficient from a stock-level regression of excess return (ret) on excess market return conducted using daily data over the prior twelve months. We require that there are at least 200 daily observations over the estimation period.
MarketSize	Log of the product of the stock price (abs(prc)) times common shares outstanding divided by 1,000 (shrout).
BookToMarket	Log of the ratio of book value-to-market value of equity (abs(prc) $\times$ shrout), where the book value of equity is equal to total assets (at) minus total liabilities (lt) plus deferred taxes (txditc, zero if missing) minus preferred stock (pstkl, pstkrv, prfstck, or zero, in that order of availability), the accounting variables are from the fiscal year end in calendar year $t-1$, and the market value of equity is from the end of December of calendar year $t-1$.

(continued on next page)

Table AI
Analysis Variables Used In Our Asset Pricing Tests (cont.)

Variable Name	Variable Definition
Momentum	Log of the compounded stock return (ret) over the period from month $t-12$ to month $t-2$. We require the stock return to be non-missing for at least nine months over the period.
Profitability	Ratio of sales (sale) net of costs of goods sold (cogs), selling, general, and administrative expenses (xsga), and interest expenses (xint) to the book value of equity, where the book value of equity is total assets (at) minus total liabilities (lt) plus deferred taxes (txditc, zero if missing) minus preferred stock (pstkl, pstkrv, prfstck, or zero, in that order of availability) and the accounting variables are from the fiscal year end in calendar year $t-1$.

Table AII

New Analysis Variables Used In Our Profit Growth Regressions

The table presents the definitions of the variables used in the panel-data profit growth regressions in Table 6. We give the variable mnemonics assigned by the data providers (CRSP and Compustat) in parentheses. When a firm's fiscal quarters do not align with calendar quarters, we assume that sales and cost of goods sold are evenly distributed over the three months underlying a fiscal quarter, while we assume that total assets are the same at the end of each. We next sum the monthly values of sales and cost of goods sold and average the monthly values of total assets by firm and calendar quarter. We calculate the control variables *Momentum*, *MarketSize*, and *BookToMarket* as described in Table AI, not repeating their definitions in this table.

Variable Name	Variable Definition
ProfitGrowth	The change in profit (saleq minus cogsq) from quarter $t-1$ to quarter t scaled by total assets (atq) from quarter $t-1$.
IndustryPriceGrowth	The ratio of the gross sales growth of an industry from quarter $t-1$ to quarter t to the gross production growth of the same industry over the same period minus one. For a given industry and firm, we estimate total sales revenues by aggregating the sales (saleq) of all firms belonging to the industry except for the firm under consideration. We estimate an industry's production growth using its industrial production index from the Federal Reserve's G.17 "Industrial Production and Capacity Utilization" database.
NewlyBuiltCapacity	A dummy variable equal to one if a firm has a positive *Construction* value in the portfolio sorts and Fama-MacBeth (1973) regressions in at least one year over the last five and else zero.
LagProfitGrowth	The one-quarter lagged value of *ProfitGrowth*.
QuarterlyReturn	The compounded stock return (ret) over calendar quarter t.

Table AIII
Industry Classifications
The table presents the 32 NAICS industries used to construct *IndustryPriceGrowth* in Table 6.

NAICS	Industry Name
315	Apparel
316	Leather and allied product
323	Printing and related support activities
324	Petroleum and coal products
3114	Fruit and vegetable preserving and specialty food
3116	Animal slaughtering and processing
3119	Other food
3121	Beverage
3221	Pulp, paper, and paperboard mills
3222	Converted paper product
3251	Basic chemical
3252	Resin, synthetic rubber, and artificial and synthetic fibers and filaments
3253	Pesticide, fertilizer, and other agricultural chemical
3254	Pharmaceutical and medicine
3256	Soap, cleaning compound, and toilet preparation
3261	Plastics product
3311,2	Iron and steel products
3314	Nonferrous metal (except aluminum) production and processing
3329	Other fabricated metal product
3331	Agriculture, construction, and mining machinery
3332	Industrial machinery
3333,9	Commercial and service industry machinery and other general purpose machinery
3334	Ventilation, heating, air-conditioning, and commercial refrigeration equipment
3343	Audio and video equipment
3345	Navigational, measuring, electromedical, and control instruments
3353	Electrical equipment

(continued on next page)

Table AIII
Industry Classifications (cont.)

NAICS	Industry Name
3359	Other electrical equipment and component
3361	Motor vehicle
3363	Motor vehicle parts
3364	Aerospace product and parts
3371	Household and institutional furniture and kitchen cabinet
3391	Medical equipment and supplies

Appendix B. Real Options Model Solution

In this appendix, we derive the quasi-closed-form solution of the real options model with time-to-build and flexible capacity introduced in Section 3. To do so, we separately value the *incremental* mature, newly-built (i.e., flexible), and under-construction production option and the growth option allowing the firm to build the production option on output increment s. Assuming that markets are complete and complete spanning holds, we obtain the values of these assets through contingent claims analysis. Having concluded the valuation, we determine that productive capacity K^* maximizing firm value net of capacity installation costs ("optimal capacity").

B.1 Valuing Mature Production Options

We first value the incremental mature production option on output increment s. That option yields a payoff of $\theta - (2\gamma + c_2)s - c_1 - f$ when switched on to produce output and a payoff of $-f$ when switched off. Moreover, it can be disinvested at a disinvestment price of d. To do the valuation, we form a portfolio long the option and short m units of an asset whose value perfectly replicates the value of demand. Denoting the value of the option to produce by $V(\theta, s)$, the value of the portfolio is given by $V(\theta, s) - m\theta$, and the change in portfolio value is given by:

$$dV(\theta, s) + \pi(\theta, s)dt - md\theta - m\delta\theta dt, \tag{B1}$$

where $\pi(\theta, s)$ is the payoff of the incremental production option. Using Itô's lemma and plugging in for θ, we can rewrite the change in portfolio value as:

$$\begin{aligned} & V_\theta(\theta, s)d\theta + \frac{1}{2}V_{\theta\theta}(\theta, s)d\theta d\theta + \pi(\theta, s)dt - \alpha m\theta dt - \sigma m\theta dW - m\delta\theta dt & \text{(B2)} \\ = \; & \alpha\theta V_\theta(\theta, s)dt + \sigma\theta V_\theta(\theta, s)dW + \frac{1}{2}\sigma^2\theta^2 V_{\theta\theta}(\theta, s)dt & \\ + \; & \pi(\theta, s)dt - \alpha m\theta dt - \sigma m\theta dW - m\delta\theta dt. & \text{(B3)} \end{aligned}$$

Setting m equal to $V_\theta(\theta, s)$, the change in portfolio value becomes deterministic and must be equal to the payoff from an equally-sized risk-free investment:

$$\frac{1}{2}\sigma^2\theta^2 V_{\theta\theta}(\theta, s)dt + \pi(\theta, s)dt - \delta\theta V_\theta(\theta, s)dt = r(V(\theta, s) - V_\theta(\theta, s)\theta)dt. \tag{B4}$$

Rearranging and dividing by dt, we obtain the ordinary differential equation:

$$\frac{1}{2}\sigma^2\theta^2 V_{\theta\theta}(\theta, s) + (r-\delta)\theta V_\theta(\theta, s) - rV(\theta, s) + \pi(\theta, s) = 0, \tag{B5}$$

which the value of the incremental option has to satisfy subject to boundary conditions.

When $\theta - (2\gamma + c_2)s - c_1 - f > -f$ or, alternatively, θ exceeds the production threshold $\theta^P \equiv (2\gamma + c_2)s + c_1$, it is optimal for the firm to switch on the option to produce output. Under these circumstances, the value of the option is given by:

$$V(\theta, s) = b_2\theta^{\beta_2} + \frac{\theta}{\delta} - \frac{(2\gamma + c_2)s + c_1}{r} - \frac{f}{r}, \tag{B6}$$

where b_2 is a free parameter and:

$$\beta_2 = -(r - \delta - \sigma^2/2)/\sigma^2 - \sqrt{(r - \delta - \sigma^2/2)^2 + 2r\sigma^2}/\sigma^2. \tag{B7}$$

Conversely, when θ falls below the production threshold θ^P, it is optimal for the firm to switch off the option, and the value of the option is given by:

$$V(\theta, s) = b_1\theta^{\beta_1} + b_3\theta^{\beta_2} - \frac{f}{r}, \tag{B8}$$

where b_1 and b_3 are free parameters and:

$$\beta_1 = -(r - \delta - \sigma^2/2)/\sigma^2 + \sqrt{(r - \delta - \sigma^2/2)^2 + 2r\sigma^2}/\sigma^2. \tag{B9}$$

Finally, when θ falls below the disinvestment threshold θ^D, it is optimal for the firm to sell off the option, and the value of the option is given by:

$$V(\theta, s) = F(\theta, s) + d, \tag{B10}$$

where $F(\theta, s)$ is the value of the option to repurchase the mature production option.

To identify the values of b_1 to b_3 and θ^D, we start by ensuring that Equation (B6) value-matches with and smooth-pastes into Equation (B8) at the production threshold θ^P:

$$\begin{aligned} b_2(\theta^P)^{\beta_2} + \frac{(\theta^P)}{\delta} - \frac{(2\gamma + c_2)s + c_1}{r} &= b_1(\theta^P)^{\beta_1} + b_3(\theta^P)^{\beta_2}, && \text{(B11)} \\ b_2\beta_2(\theta^P)^{\beta_2 - 1} + \frac{1}{\delta} &= b_1\beta_1(\theta^P)^{\beta_1 - 1} + b_3\beta_2(\theta^P)^{\beta_2 - 1}. && \text{(B12)} \end{aligned}$$

Solving Equations (B11) and (B12) for b_1 and $(b_2 - b_3)$, we obtain:

$$\begin{aligned} b_1 &= \frac{r - \beta_2(r - \delta)}{r\delta(\beta_1 - \beta_2)}[(2\gamma + c_2)s + c_1]^{1-\beta_1}, && \text{(B13)} \\ (b_2 - b_3) &= \frac{r - \beta_1(r - \delta)}{r\delta(\beta_1 - \beta_2)}[(2\gamma + c_2)s + c_1]^{1-\beta_2}. && \text{(B14)} \end{aligned}$$

To identify the remaining parameter values, we need to value the option to repurchase the mature option to produce. Using the same argumentation as above, the value of that option, $F(\theta, s)$, must fulfill the ordinary differential equation:

$$\frac{1}{2}\sigma^2\theta^2 F_{\theta\theta}(\theta, s) + (r - \delta)\theta F_\theta(\theta, s) - rF(\theta, s) = 0. \tag{B15}$$

Denote the demand level at or above which the firm exercises the option to repurchase the mature production option (i.e., the investment threshold) by $\theta^\perp$. When demand is below that threshold, the value of the option to repurchase the production option is equal to:

$$F(\theta, s) = a\theta^{\beta_1}, \tag{B16}$$

where a is a free parameter. In the opposite case, it is equal to:

$$F(\theta, s) = V(\theta, s) - l, \tag{B17}$$

where l is the unit repurchase cost of the mature production option.

Plugging Equation (B16) into Equation (B10) and letting Equation (B8) value-match with and smooth-paste into Equation (B10) at the disinvestment threshold θ^D, we obtain:

$$\begin{aligned} b_1(\theta^D)^{\beta_1} + b_3(\theta^D)^{\beta_2} - \frac{f}{r} &= a(\theta^D)^{\beta_1} + d, & \text{(B18)} \\ b_1\beta_1(\theta^D)^{\beta_1 - 1} + b_3\beta_2(\theta^D)^{\beta_2 - 1} &= a\beta_1(\theta^D)^{\beta_1 - 1}. & \text{(B19)} \end{aligned}$$

Conditional on the value of a, we solve Equations (B18) and (B19) for b_3 and θ^D, yielding:

$$\begin{aligned} \theta^D &= \left[\frac{\beta_2(f/r + d)}{(a - b_1)(\beta_1 - \beta_2)}\right]^{\frac{1}{\beta_1}}, & \text{(B20)} \\ b_3 &= \frac{\beta_1(f/r + d)}{\beta_1 - \beta_2}\left[\frac{\beta_2(f/r + d)}{(a - b_1)(\beta_1 - \beta_2)}\right]^{-\frac{\beta_2}{\beta_1}} & \text{(B21)} \end{aligned}$$

which, in combination with Equation (B14), also yields b_2.

To identify a and $\theta^{\perp}$, we ensure that Equation (B16) value-matches with and smooth-pastes into Equation (B17) at the investment threshold, yielding:

$$\begin{aligned} b_2(\theta^{\perp})^{\beta_2} + \frac{(\theta^{\perp})}{\delta} - \frac{(2\gamma + c_2)K + c_1}{r} - \frac{f}{r} - l &= a(\theta^{\perp})^{\beta_1}, & \text{(B22)} \\ b_2\beta_2(\theta^{\perp})^{\beta_2 - 1} + \frac{1}{\delta} &= a\beta_1(\theta^{\perp})^{\beta_1 - 1}. & \text{(B23)} \end{aligned}$$

Conditional on the value of the investment threshold $\theta^{\perp}$, we find that:

$$a = b_2 \frac{\beta_2}{\beta_1} (\theta^{\perp})^{\beta_2 - \beta_1} + \frac{1}{\delta \beta_1} (\theta^{\perp})^{1-\beta_1}. \tag{B24}$$

Plugging Equation (B24) into Equation (B22), Equation (B22) becomes an implicit function of the investment threshold $\theta^{\perp}$ alone, which can be numerically solved for $\theta^{\perp}$.

B.2 Valuing Newly-Built Productions Options

We next value the newly-built production option on output increment s. A newly-build production option yields the same payoff as its mature counterpart when it is switched on or off to produce the standard output good. To reflect, however, that modern production technologies tend to be more flexible than more mature technologies, we assume that newly-built production options also have an alternative use. In particular, they can be costlessly switched to produce one unit per time of an alternative output good, which, for simplicity, makes a constant profit of $\theta_A - f$, where θ_A is the selling price net of variable production costs. Since as time passes modern technologies become mature, the ability to switch a newly-built production option to produce the alternative output good disappears with a probability of λ per time unit.

As before, we also use contingent claims analysis to value the incremental newly-built production option. To do so, we again form a portfolio long the incremental option and short m units of an asset whose value perfectly replicates the value of demand. Denoting the value of the newly-built option to produce by $V^{nb}(\theta, s)$, we can write the value of the portfolio as $V^{nb}(\theta, s) - m\theta$, while we can write the change in portfolio value as:

$$dV^{nb}(\theta, s) + \pi(\theta, s)dt - md\theta - m\delta\theta dt, \tag{B25}$$

Using Itô's lemma and plugging in for θ, we can rewrite the change in portfolio value as:

$$\begin{aligned}
& V_\theta^{nb}(\theta,s)d\theta + \frac{1}{2}V_{\theta\theta}^{nb}(\theta,s)d\theta d\theta + \pi(\theta,s)dt \\
+ \; & \mathbb{I}(\lambda)(V(\theta,s) - V^{nb}(\theta,s)) - \alpha m\theta dt - \sigma m\theta dW - m\delta\theta dt \qquad \text{(B26)} \\
= \; & \alpha\theta V_\theta^{nb}(\theta,s)dt + \sigma\theta V_\theta^{nb}(\theta,s)dW + \frac{1}{2}\sigma^2\theta^2 V_{\theta\theta}^{nb}(\theta,s)dt + \pi(\theta,s)dt \\
+ \; & \mathbb{I}(\lambda)(V(\theta,s) - V^{nb}(\theta,s)) - \alpha m\theta dt - \sigma m\theta dW - m\delta\theta dt, \qquad \text{(B27)}
\end{aligned}$$

where $\mathbb{I}(\lambda)$ is an indicator variable equal to one when the newly-build production option becomes mature and else zero. Setting m equal to $V_\theta^{nb}(\theta,s)$, we are left with:

$$\frac{1}{2}\sigma^2\theta^2 V_{\theta\theta}^{nb}(\theta,s)dt - \delta\theta V_\theta^{nb}(\theta,s)dt + \pi(\theta,s)dt + \mathbb{I}(\lambda)(V(\theta,s) - V^{nb}(\theta,s)). \qquad \text{(B28)}$$

While Equation (B28) is not deterministic, its expectation is equal to the payoff from an equally-sized risk-free investment if the probability of the newly-built production option becoming a mature production option is idiosyncratic. In that case, we can write:

$$\begin{aligned}
& \frac{1}{2}\sigma^2\theta^2 V_{\theta\theta}^{nb}(\theta,s)dt - \delta\theta V_\theta^{nb}(\theta,s)dt + \pi(\theta,s)dt + \lambda(V(\theta,s) - V^{nb}(\theta,s))dt \\
= \; & r(V^{nb}(\theta,s) - V_\theta^{nb}(\theta,s)\theta)dt. \qquad \text{(B29)}
\end{aligned}$$

Rearranging and dividing by dt, we obtain the ordinary differential equation that a newly-built production option needs to satisfy subject to boundary conditions:

$$\frac{1}{2}\sigma^2\theta^2 V_{\theta\theta}^{nb}(\theta,s) + (r-\delta)\theta V_\theta^{nb}(\theta,s) - (r+\lambda)V^{nb}(\theta,s) + \pi(\theta,s) + \lambda V(\theta,s) = 0. \qquad \text{(B30)}$$

When $\theta - (2\gamma + c_2)K - c_1 - f > \theta_A - f$ or θ exceeds the alternative usage threshold $\theta^\diamond \equiv (2\gamma + c_2)K + c_1 + \theta_A$, it is optimal for the firm to use the newly-built production option to produce the standard output. In addition, doing so continues to be optimal if the newly-built production option becomes a mature production option. In that case, the value of the newly-built production option is given by:

$$V^{nb}(\theta, s) = b_2'\theta^{\beta_2'} + b_2\theta^{\beta_2} + \frac{\theta}{\delta} - \frac{[(2\gamma + c_2)K + c_1] + f}{r}, \tag{B31}$$

where b_2' is a free parameter and

$$\beta_2' = -(r - \delta - \sigma^2/2)/\sigma^2 - \sqrt{(r - \delta - \sigma^2/2)^2 + 2(r + \lambda)\sigma^2}/\sigma^2. \tag{B32}$$

When $\theta_A - f > \theta - (2\gamma + c_2)K - c_1 - f > -f$ or, alternatively, $\theta^\diamond > \theta > (2\gamma + c_2)K + c_1$, it is optimal for the firm to use the newly-built production option to produce the alternative output, but to switch to producing the standard output if the newly-build production option becomes a mature production option. In that case, the value of the newly-built production option is equal to:

$$V^{nb}(\theta, s) = b_1'\theta^{\beta_1'} + b_3'\theta^{\beta_2'} + b_2\theta^{\beta_2} - \frac{\theta}{\delta + \lambda} + \frac{\theta_A + (2\gamma + c_2)K + c_1}{r + \lambda} + \frac{\theta}{\delta} - \frac{(2\gamma + c_2)K + c_1 + f}{r}, \tag{B33}$$

where b_1' and b_3' are free parameters and:

$$\beta_1' = -(r - \delta - \sigma^2/2)/\sigma^2 + \sqrt{(r - \delta - \sigma^2/2)^2 + 2(r + \lambda)\sigma^2}/\sigma^2. \tag{B34}$$

When $\theta_A - f > -f > \theta - (2\gamma + c_2)K - c_1 - f > \theta^D$ or $\theta^D < \theta < (2\gamma + c_2)K + c_1$, it is still optimal for the firm to use the newly-built production option to produce the alternative output, but to now switch off the option if the newly-build production option becomes a mature production option. In that case, the value of the newly-built production option is equal to:

$$V^{nb}(\theta, s) = b_4'\theta^{\beta_1'} + b_5'\theta^{\beta_2'} + \frac{\theta_A}{r + \lambda} + b_1\theta^{\beta_1} + b_3\theta^{\beta_2} - \frac{f}{r}, \tag{B35}$$

where b_4' and b_5' are free parameters. Finally, when $\theta < \theta^D$, it is still optimal for the firm to use the newly-built production option to produce the alternative output, but to disinvest the option at the disinvestment price d if the newly-build production option becomes a mature production option. In that case, the value of the newly-built option is equal to:

$$V^{nb}(\theta, s) = b_6'\theta^{\beta_1'} + \frac{\theta_A - f}{r+\lambda} + a\theta^{\beta_1} + \frac{\lambda d}{r+\lambda}, \tag{B36}$$

where b_6 is a free parameter. Excluding a $\theta^{\beta_2'}$ term, Equation (B36) implicitly assumes that the value of the alternative use is so high that it is never optimal for the firm to disinvest a newly-built production option (which would, e.g., be the case if disinvesting a newly-built option implied that the firm only regained the option to purchase the equivalent mature option and $\theta_A - f + \lambda d - (r+\lambda)\bar{d} > 0$, with $\bar{d}$ the disinvestment price of the newly-built option).

To determine the values of b_1' and $(b_2' - b_3')$, we ensure that Equation (B31) value-matches with and smooth-pastes into Equation (B33) at the alternative use threshold $\theta^\diamond$:

$$\begin{aligned} b_2'(\theta^\diamond)^{\beta_2'} &= b_1'(\theta^\diamond)^{\beta_1'} + b_3'(\theta^\diamond)^{\beta_2'} - \frac{(\theta^\diamond)}{\delta+\lambda} + \frac{l + (2\gamma + c)K + c_1}{r+\lambda}, && \text{(B37)} \\ b_2'\beta_2'(\theta^\diamond)^{\beta_2'-1} &= b_1'\beta_1'(\theta^\diamond)^{\beta_1'-1} + b_3'\beta_2'(\theta^\diamond)^{\beta_2'-1} - \frac{1}{\delta+\lambda}. && \text{(B38)} \end{aligned}$$

Solving Equations (B37) and (B38) for b_1' and $(b_2' - b_3')$, we obtain:

$$\begin{aligned} b_1' &= \frac{(r+\lambda) - \beta_2'(r-\delta)}{(r+\lambda)(\delta+\lambda)(\beta_1' - \beta_2')}(\theta^\diamond)^{1-\beta_1'}, && \text{(B39)} \\ (b_2' - b_3') &= \frac{(r+\lambda) - \beta_1'(r-\delta)}{(r+\lambda)(\delta+\lambda)(\beta_1' - \beta_2')}(\theta^\diamond)^{1-\beta_2'}. && \text{(B40)} \end{aligned}$$

To determine the values of $(b_1' - b_4')$ and $(b_3' - b_5')$, we ensure that Equation (B33) value-matches with and smooth-pastes into Equation (B35) at the production threshold θ^P:

$$\begin{aligned}
& b_1'(\theta^P)^{\beta_1'} + b_3'(\theta^P)^{\beta_2'} + b_2(\theta^P)^{\beta_2} - \frac{(\theta^P)}{\delta+\lambda} + \frac{(2\gamma+c)K+c_1}{r+\lambda} \\
+ \quad & \frac{(\theta^P)}{\delta} - \frac{(2\gamma+c_2)K+c_1}{r} = b_4'(\theta^P)^{\beta_1'} + b_5'(\theta^P)^{\beta_2'} + b_1(\theta^P)^{\beta_1} + b_3(\theta^P)^{\beta_2}, \qquad \text{(B41)} \\
& b_1'\beta_1'(\theta^P)^{\beta_1'-1} + b_3'\beta_2'(\theta^P)^{\beta_2'-1} + b_2\beta_2(\theta^P)^{\beta_2-1} - \frac{1}{\delta+\lambda} + \frac{1}{\delta} \\
= \quad & b_4'\beta_1'(\theta^P)^{\beta_1'-1} + b_5'\beta_2'(\theta^P)^{\beta_2'-1} + b_1\beta_1(\theta^P)^{\beta_1-1} + b_3\beta_2(\theta^P)^{\beta_2-1}. \qquad \text{(B42)}
\end{aligned}$$

Solving Equations (B41) and (B42) for $(b_1' - b_4')$ and $(b_3' - b_5')$, we obtain:

$$\begin{aligned}
(b_1' - b_4') &= \frac{b_1(\beta_2'-\beta_1)}{\beta_2'-\beta_1'}(\theta^P)^{\beta_1-\beta_1'} + \frac{(b_2-b_3)(\beta_2-\beta_2')}{\beta_2'-\beta_1'}(\theta^P)^{\beta_2-\beta_1'} \\
&+ \lambda\frac{r(r+\lambda) - \beta_2'(r(r+\lambda)-\delta(\delta+\lambda))}{r\delta(\delta+\lambda)(r+\lambda)(\beta_2'-\beta_1')}(\theta^P)^{1-\beta_1'}, \qquad \text{(B43)} \\
(b_3' - b_5') &= \frac{b_1(\beta_1-\beta_1')}{\beta_2'-\beta_1'}(\theta^P)^{\beta_1-\beta_2'} + \frac{(b_2-b_3)(\beta_1'-\beta_2)}{\beta_2'-\beta_1'}(\theta^P)^{\beta_2-\beta_2'} \\
&- \lambda\frac{r(r+\lambda) - \beta_1'(r(r+\lambda)-\delta(\delta+\lambda))}{r\delta(\delta+\lambda)(r+\lambda)(\beta_2'-\beta_1')}(\theta^P)^{1-\beta_2'}. \qquad \text{(B44)}
\end{aligned}$$

To determine the values of $(b_4' - b_6')$ and b_5', we finally ensure that Equation (B35) value-matches with and smooth-pastes into Equation (B36) at the disinvestment threshold θ^D:

$$\begin{aligned}
b_4'\theta^{\beta_1'} + b_5'\theta^{\beta_2'} + b_1\theta^{\beta_1} + b_3\theta^{\beta_2} - \frac{f}{r} &= b_6'\theta^{\beta_1'} - \frac{f}{r+\lambda} + a\theta^{\beta_1} + \frac{\lambda d}{r+\lambda}, \qquad \text{(B45)} \\
b_4'\beta_1'\theta^{\beta_1'-1} + b_5'\beta_2'\theta^{\beta_2'-1} + b_1\beta_1\theta^{\beta_1-1} + b_3\beta_2\theta^{\beta_2-1} &= b_6'\beta_1'\theta^{\beta_1'-1} + a\beta_1\theta^{\beta_1-1}. \qquad \text{(B46)}
\end{aligned}$$

Solving Equations (B45) and (B46) for $(b_4' - b_6')$ and b_5', we obtain:

$$\begin{aligned}
(b_4' - b_6') &= (a-b_1)\frac{(\beta_1-\beta_2')}{(\beta_1'-\beta_2')}(\theta^D)^{\beta_1-\beta_1'} - b_3\frac{(\beta_2-\beta_2')}{(\beta_1'-\beta_2')}(\theta^D)^{\beta_2-\beta_1'} \\
&- \frac{\beta_2'}{(\beta_1'-\beta_2')}\left(\frac{\lambda f}{r(r+\lambda)} + \frac{\lambda d}{(r+\lambda)}\right)(\theta^D)^{-\beta_1'}, \qquad \text{(B47)}
\end{aligned}$$

$$
\begin{aligned}
b_5' &= (a-b_1)\frac{(\beta_1'-\beta_1)}{(\beta_1'-\beta_2')}(\theta^D)^{\beta_1-\beta_2'} - b_3\frac{(\beta_1'-\beta_2)}{(\beta_1'-\beta_2')}(\theta^D)^{\beta_2-\beta_2'} \\
&+ \frac{\beta_1'}{(\beta_1'-\beta_2')}\left(\frac{\lambda f}{r(r+\lambda)} + \frac{\lambda d}{(r+\lambda)}\right)(\theta^D)^{-\beta_2'}. \qquad \text{(B48)}
\end{aligned}
$$

Using Equation (B39) in combination with (B43), we are able to recover b_4', which we use in Equation (B47) to recover b_6'. Using Equation (B48) in combination with (B44), we are able to recover b_3', which we use in Equation (B40) to recover b_2'.

B.3 Valuing Production Options-Under-Construction

We next value the production option-under-construction on output increment s. That option cannot produce output over a period of length $\bar{T}$ at the start of construction (initial time-to-build) and a period of length $\bar{T}(s)$ during construction (remaining time-to-build), but also does not incur costs over the construction period. At the end of the construction period, the production option-under-construction becomes a newly-built production option. Again using contingent claims analysis, we form a portfolio long the production option-under-construction and short m units of an asset whose value perfectly replicates the value of demand. Denoting the value of the production option-under-construction by $V^{uc}(\theta, \bar{T}(s), s)$, we can write the value of the portfolio as $V^{uc}(\theta, \bar{T}(s), s) - m\theta$, while we can write the change in portfolio value as:

$$
dV^{uc}(\theta, \bar{T}(s), s) - md\theta - m\delta\theta dt. \qquad \text{(B49)}
$$

Using Itô's Lemma and plugging in for θ, we obtain:

$$
\begin{aligned}
& V^{uc}_{\theta}(\theta, \bar{T}(s), s)d\theta + \frac{1}{2}V^{uc}_{\theta\theta}(\theta, \bar{T}(s), s)d\theta d\theta \\
+ \;& V^{uc}_{\bar{T}}(\theta, \bar{T}(s), s)d\bar{T} - \alpha m\theta dt - \sigma m\theta dW - m\delta\theta dt \qquad \text{(B50)}
\end{aligned}
$$

$$
\begin{aligned}
&= \alpha\theta V^{uc}_{\theta}(\theta,\bar{T}(s),s)dt + \sigma\theta V^{uc}_{\theta}(\theta,\bar{T}(s),s)dW + \frac{1}{2}\sigma^2\theta^2 V^{uc}_{\theta\theta}(\theta,\bar{T}(s),s)dt \\
&+ V^{uc}_{\bar{T}}(\theta,\bar{T}(s),s)d\bar{T} - \alpha m\theta dt - \sigma m\theta dW - m\delta\theta dt, \qquad \text{(B51)}
\end{aligned}
$$

Noting that $d\bar{T} = -dt$ and setting $m = V^{uc}_{\theta}(\theta,\bar{T}(s),s)$, the portfolio payoff becomes deterministic and thus needs to be equal to the payoff from an equally-sized risk-free investment:

$$
\begin{aligned}
&\frac{1}{2}\sigma^2\theta^2 V^{uc}_{\theta\theta}(\theta,\bar{T}(s),s)dt - V^{uc}_{\bar{T}}(\theta,\bar{T}(s),s)dt - \delta\theta V^{uc}_{\theta}(\theta,\bar{T}(s),s)dt \\
&= r(V^{uc}(\theta,\bar{T}(s),s) - \theta V^{uc}_{\theta}(\theta,\bar{T}(s),s))dt, \qquad \text{(B52)}
\end{aligned}
$$

Dividing by dt and rearranging, we obtain the partial differential equation:

$$
\frac{1}{2}\sigma^2\theta^2 V^{uc}_{\theta\theta}(\theta,\bar{T}(s),s) + (r-\delta)\theta V^{uc}_{\theta}(\theta,\bar{T}(s),s) - rV^{uc}(\theta,\bar{T}(s),s) - V^{uc}_{\bar{T}}(\theta,\bar{T}(s),s) = 0, \qquad \text{(B53)}
$$

which $V^{uc}(\theta,\bar{T}(s),s)$ must obey subject to boundary conditions.

Let s, n, and p be arbitrary constants. We then note that both:

$$
V^{uc}(\theta,\bar{T}(s),s) = s\theta^n e^{-\delta_1(n)\bar{T}(s)} N\left[\frac{\ln\left(\frac{\theta e^{-\delta_2(n)\bar{T}(s)}}{p}\right) + (r+\frac{1}{2}\sigma^2)\bar{T}(s)}{\sigma\sqrt{\bar{T}(s)}}\right] \qquad \text{(B54)}
$$

and

$$
V^{uc}(\theta,\bar{T}(s),s) = s\theta^n e^{-\delta_1(n)\bar{T}(s)} N\left[-\frac{\ln\left(\frac{\theta e^{-\delta_2(n)\bar{T}(s)}}{p}\right) + (r+\frac{1}{2}\sigma^2)\bar{T}(s)}{\sigma\sqrt{\bar{T}(s)}}\right], \qquad \text{(B55)}
$$

with $\delta_1(n) = r - (r-\delta)n - \frac{1}{2}\sigma^2 n(n-1)$ and $\delta_2(n) = \delta - \sigma^2(n-1)$, satisfy the partial differential equation. We choose s, n, and p to fulfill the boundary conditions. As demand θ increases to infinity, $V^{uc}(\theta,\bar{T}(s),s)$ must converge to $\frac{\theta}{\delta} - \frac{[(2\gamma+c_2)s+c_1]+f}{r}$ discounted over the time-to-build $\bar{T}(s)$. As demand θ decreases to zero, $V^{uc}(\theta, \bar{T}(s), s)$ must converge to $\frac{\theta_A - f}{r+\lambda} + \frac{\lambda d}{r+\lambda}$ discounted over the time-to-build $\bar{T}(s)$. As the time-to-build $\bar{T}(s)$ converges to zero, it must hold that:

$$
\begin{aligned}
\lim_{\bar{T}(s)\to 0} V^{uc}(\theta, \bar{T}(s), s) &= b_2'\theta^{\beta_2'} + b_2\theta^{\beta_2} + \frac{\theta}{\delta} - \frac{(2\gamma + c_2)s + c_1 + f}{r} \quad \text{for } \theta > \theta^{\diamond}, && \text{(B56)}\\
\lim_{\bar{T}(s)\to 0} V^{uc}(\theta, \bar{T}(s), s) &= b_1'\theta^{\beta_1'} + b_3'\theta^{\beta_2'} + b_2\theta^{\beta_2} - \frac{\theta}{\delta+\lambda} + \frac{\theta_A + (2\gamma + c_2)s + c_1}{r+\lambda}\\
&+ \frac{\theta}{\delta} - \frac{(2\gamma + c_2)s + c_1 + f}{r} \quad \text{for } \theta^{\diamond} \geq \theta > \theta^P, && \text{(B57)}\\
\lim_{\bar{T}(s)\to 0} V^{uc}(\theta, \bar{T}(s), s) &= b_4'\theta^{\beta_1'} + b_5'\theta^{\beta_2'} + \frac{\theta_A}{r+\lambda} + b_1\theta^{\beta_1} + b_3\theta^{\beta_2} - \frac{f}{r} \quad \text{for } \theta^P \geq \theta > \theta^D, && \text{(B58)}\\
\lim_{\bar{T}(s)\to 0} V^{uc}(\theta, \bar{T}(s), s) &= b_6'\theta^{\beta_1'} + \frac{\theta_A - f}{r+\lambda} + a\theta^{\beta_1} + \frac{\lambda d}{r+\lambda} \quad \text{for } \theta^D \geq \theta. && \text{(B59)}
\end{aligned}
$$

For arbitrary constants p_1 and p_2, we now define:

$$
\begin{aligned}
\Theta(\theta, n, p_1, p_2) \equiv\ & e^{-\delta_1(n)\bar{T}(s)}\Bigg(N\left[\frac{\ln\left(\frac{\theta e^{-\delta_2(n)\bar{T}(s)}}{p_1}\right) + (r + \frac{1}{2}\sigma^2)\bar{T}(s)}{\sigma\sqrt{\bar{T}(s)}}\right]\\
&- N\left[\frac{\ln\left(\frac{\theta e^{-\delta_2(n)\bar{T}(s)}}{p_2}\right) + (r + \frac{1}{2}\sigma^2)\bar{T}(s)}{\sigma\sqrt{\bar{T}(s)}}\right]\Bigg), \qquad \text{(B60)}
\end{aligned}
$$

where N is the standard normal cumulative density function. We can then write the value of the production option under construction, $V^{uc}(\theta, \bar{T}(s), s)$, as the sum of four terms:

$$
V^{uc}(\theta, \bar{T}(s), s) = V_1^{uc}(\theta, \bar{T}(s), s) + V_2^{uc}(\theta, \bar{T}(s), s) + V_3^{uc}(\theta, \bar{T}(s), s) + V_4^{uc}(\theta, \bar{T}(s), s), \quad \text{(B61)}
$$

where:

$$
\begin{aligned}
V_1^{uc}(\theta, \bar{T}(s), s) &= b_2'\theta^{\beta_2'}\Theta(\theta, \beta_2', \theta^{\diamond}, \infty) + b_2\theta^{\beta_2}\Theta(\theta, \beta_2, \theta^{\diamond}, \infty)\\
&+ \frac{\theta}{\delta}\Theta(\theta, 1, \theta^{\diamond}, \infty) - \frac{(2\gamma + c_2)K + c_1 + f}{r}\Theta(\theta, 0, \theta^{\diamond}, \infty), \qquad \text{(B62)}
\end{aligned}
$$

$$\begin{aligned}
V_2^{uc}(\theta, \bar{T}(s), s) &= b_1'\theta^{\beta_1'}\Theta(\theta, \beta_1', \theta^P, \theta^\diamond) + b_3'\theta^{\beta_2'}\Theta(\theta, \beta_2', \theta^P, \theta^\diamond) + b_2\theta^{\beta_2}\Theta(\theta, \beta_2, \theta^P, \theta^\diamond) \\
&- \frac{\theta}{\delta + \lambda}\Theta(\theta, 1, \theta^P, \theta^\diamond) + \frac{l + (2\gamma + c_2)K + c_1}{r + \lambda}\Theta(\theta, 0, \theta^P, \theta^\diamond) \\
&+ \frac{\theta}{\delta}\Theta(\theta, 1, \theta^P, \theta^\diamond) - \frac{(2\gamma + c_2)K + c_1 + f}{r}\Theta(\theta, 0, \theta^P, \theta^\diamond), \qquad \text{(B63)} \\
V_3^{uc}(\theta, \bar{T}(s), s) &= b_4'\theta^{\beta_1'}\Theta(\theta, \beta_1', \theta^D, \theta^P) + b_5'\theta^{\beta_2'}\Theta(\theta, \beta_2', \theta^D, \theta^P) + \frac{l}{r + \lambda}\Theta(\theta, 0, \theta^D, \theta^P) \\
&+ b_1\theta^{\beta_1}\Theta(\theta, \beta_1, \theta^D, \theta^P) + b_3\theta^{\beta_2}\Theta(\theta, \beta_2, \theta^D, \theta^P) - \frac{f}{r}\Theta(\theta, 0, \theta^D, \theta^P), \qquad \text{(B64)}
\end{aligned}$$

and

$$\begin{aligned}
\bar{V}_4^{uc}(\theta, \bar{T}(s), s) &= b_6'\theta^{\beta_1'}\Theta(\theta, \beta_1', 0, \theta^D) + \frac{l - f}{r + \lambda}\Theta(\theta, 0, 0, \theta^D) \\
&+ a\theta^{\beta_1}\Theta(\theta, \beta_1, 0, \theta^D) + \frac{\lambda d}{r + \lambda}\Theta(\theta, 0, 0, \theta^D). \qquad \text{(B65)}
\end{aligned}$$

B.4 Valuing Growth Options

We finally value the growth option allowing the firm to build the production option on output increment s at a unit investment cost of k. To do so, denote the value of that growth option by $G(\theta, \bar{T}, s)$ and the demand level at which the firm exercises the growth option by θ^*. We can interpret θ^* as the optimal investment threshold. Assuming that demand is below the optimal investment threshold, the value of the growth option is equal to:

$$G(\theta, \bar{T}, s) = e\theta^{\beta_1}, \qquad \text{(B66)}$$

where e is a free parameter. In the opposite case, it is equal to:

$$G(\theta, \bar{T}, s) = V^{uc}(\theta, \bar{T}, s) - k. \qquad \text{(B67)}$$

To obtain a and θ^*, we ensure that the value of the production option-under-construction in Equation (B61) value-matches with and also smooth pastes into the value of the growth option in Equation (B66) at the optimal investment threshold:

$$e(\theta^*)^{\beta_1} = V^{uc}(\theta^*, \bar{T}, s) - k, \quad \text{(B68)}$$

$$e\beta_1(\theta^*)^{\beta_1 - 1} = \frac{\partial V^{uc}(\theta^*, \bar{T}, s)}{\partial \theta^*}, \quad \text{(B69)}$$

where:

$$\frac{\partial V^{uc}(\theta, \bar{T}, s)}{\partial \theta} = \frac{\partial V_1^{uc}(\theta, \bar{T}, s)}{\partial \theta} + \frac{\partial V_2^{uc}(\theta, \bar{T}, s)}{\partial \theta} + \frac{\partial V_3^{uc}(\theta, \bar{T}, s)}{\partial \theta} + \frac{\partial V_4^{uc}(\theta, \bar{T}, s)}{\partial \theta}, \quad \text{(B70)}$$

$$\begin{aligned}
\frac{\partial V_1^{uc}(\theta, \bar{T}, s)}{\partial \theta} &= b_2' \theta^{\beta_2' - 1} \left(\beta_2' \Theta(\theta, \beta_2', \theta^\diamond, \infty) + Z(\theta, \beta_2', \theta^\diamond, \infty) \right) \\
&+ b_2 \theta^{\beta_2 - 1} \left(\beta_2 \Theta(\theta, \beta_2, \theta^\diamond, \infty) + Z(\theta, \beta_2, \theta^\diamond, \infty) \right) \\
&+ \frac{1}{\delta} \left(\Theta(\theta, 1, \theta^\diamond, \infty) + Z(\theta, 1, \theta^\diamond, \infty) \right) \\
&- \frac{[(2\gamma + c_2)s + c_1] + f}{r} \frac{Z(\theta, 0, \theta^\diamond, \infty)}{\theta}, \quad \text{(B71)}
\end{aligned}$$

$$\begin{aligned}
\frac{\partial V_2^{uc}(\theta, \bar{T}, s)}{\partial \theta} &= b_1' \theta^{\beta_1' - 1} \left(\beta_1' \Theta(\theta, \beta_1', \theta^P, \theta^\diamond) + Z(\theta, \beta_1', \theta^P, \theta^\diamond) \right) \\
&+ b_3' \theta^{\beta_2' - 1} \left(\beta_2' \Theta(\theta, \beta_2', \theta^P, \theta^\diamond) + Z(\theta, \beta_2', \theta^P, \theta^\diamond) \right) \\
&+ b_2 \theta^{\beta_2 - 1} \left(\beta_2 \Theta(\theta, \beta_2, \theta^P, \theta^\diamond) + Z(\theta, \beta_2, \theta^P, \theta^\diamond) \right) \\
&- \frac{1}{\delta + \lambda} \left(\Theta(\theta, 1, \theta^P, \theta^\diamond) + Z(\theta, 1, \theta^P, \theta^\diamond) \right) \\
&+ \frac{[(2\gamma + c_2)s + c_1] + l}{r + \lambda} \frac{Z(\theta, 0, \theta^P, \theta^\diamond)}{\theta} \\
&+ \frac{1}{\delta} \left(\Theta(\theta, 1, \theta^P, \theta^\diamond) + Z(\theta, 1, \theta^P, \theta^\diamond) \right) \\
&- \frac{[(2\gamma + c_2)s + c_1] + f}{r} \frac{Z(\theta, 0, \theta^P, \theta^\diamond)}{\theta}, \quad \text{(B72)}
\end{aligned}$$

$$
\begin{aligned}
\frac{\partial V_3^{uc}(\theta,\bar{T},s)}{\partial\theta} &= b_4'\theta^{\beta_1'-1}\left(\beta_1'\Theta(\theta,\beta_1',\theta^D,\theta^P)+Z(\theta,\beta_1',\theta^D,\theta^P)\right) \\
&+ b_5'\theta^{\beta_2'-1}\left(\beta_2'\Theta(\theta,\beta_2',\theta^D,\theta^P)+Z(\theta,\beta_2',\theta^D,\theta^P)\right) \\
&+ \left(\frac{l}{r+\lambda}-\frac{f}{r}\right)\frac{Z(\theta,0,\theta^D,\theta^P)}{\theta} \\
&+ b_1\theta^{\beta_1-1}\left(\beta_1\Theta(\theta,\beta_1,\theta^D,\theta^P)+Z(\theta,\beta_1,\theta^D,\theta^P)\right) \\
&+ b_3\theta^{\beta_2-1}\left(\beta_2\Theta(\theta,\beta_2,\theta^D,\theta^P)+Z(\theta,\beta_2,\theta^D,\theta^P)\right), \qquad \text{(B73)}
\end{aligned}
$$

$$
\begin{aligned}
\frac{\partial V_4^{uc}(\theta,\bar{T},s)}{\partial\theta} &= b_6'\theta^{\beta_1'-1}\left(\beta_1'\Theta(\theta,\beta_1',0,\theta^D)+Z(\theta,\beta_1',0,\theta^D)\right) \\
&+ \left(\frac{(l-f)+\lambda d}{r+\lambda}\right)\frac{Z(\theta,0,0,\theta^D)}{\theta} \\
&+ a\theta^{\beta_1-1}\left(\beta_1\Theta(\theta,\beta_1,0,\theta^D)+Z(\theta,\beta_1,0,\theta^D)\right), \qquad \text{(B74)}
\end{aligned}
$$

and

$$
Z(\theta,n,p_1,p_2)\equiv\frac{e^{-\delta_1(n)\bar{T}}}{\sigma\sqrt{\bar{T}}}\left(\phi\left[\frac{\ln\left(\frac{\theta e^{-\delta_2(n)\bar{T}}}{p_1}\right)+(r+\frac{1}{2}\sigma^2)\bar{T}}{\sigma\sqrt{\bar{T}}}\right]-\phi\left[\frac{\ln\left(\frac{\theta e^{-\delta_2(n)\bar{T}}}{p_2}\right)+(r+\frac{1}{2}\sigma^2)\bar{T}}{\sigma\sqrt{\bar{T}}}\right]\right), \qquad \text{(B75)}
$$

where ϕ is the standard normal probability density function. Since it is impossible to analytically solve Equations (B68) and (B69) for e and θ^*, we do so numerically.

B.5 Determining a Firm's Optimal Capacity

Given demand θ, we define a firm's optimal capacity K^* as that K value satisfying:

$$
V^{uc}(\theta,\bar{T},K^*)=k+G(\theta,\bar{T},K^*), \qquad \text{(B76)}
$$

ensuring that the marginal benefit from exercising the growth option on output increment K (which is obtaining the equivalent under-production option) is identical to the marginal cost from doing so (which is paying the investment cost and sacrificing the growth option).