Investment Shocks and Cross-sectional Returns: An Investment-based Approach

Abstract

We propose a new measure of firms' exposure to investment shocks—i.e., shocks that affect firms' cost of investment—and study its implication for cross-sectional returns. Theoretically, we show that a firm's exposure to investment shocks is determined by its discounted future investment expenditures scaled by its current market value. Unlike existing measures, which rely on noisy proxies of investment shocks, ours can be computed directly from observable investment data. Empirically, we find that across book-to-market portfolios, our investment-based measure of risk exposure to investment shocks has the opposite pattern to that of existing proxy-based measures. This finding has profound implications for the pricing effect of investment shocks. According to our measure, value firms have a higher (as opposed to lower) exposure to investment shocks suggesting that a positive (as opposed to negative) price of risk for investment shocks is required to explain the value premium.

JEL Classification Codes: E22; G12; O30

Keywords: Investment shocks; Capital expenditures; Value premium

1 Introduction

Capital-embodied, or investment-specific, technology shocks (hereafter referred to as "investment shocks" or, in short, "IST shocks") are technological innovations that materialize through the creation of new capital stock. Since the work of Solow (1960), these investment shocks have been recognized as an important determinant of economic growth and business cycle fluctuations. More recently, financial economists have stressed their importance for explaining cross-sectional and time-series properties of returns. Unfortunately, IST shocks are not directly observable and are commonly measured through noisy proxies constructed from either macroeconomic or financial data. Existing studies find that proxies built on macro data typically exhibit very low correlation with proxies built on financial data, suggesting that our understanding of the effects of IST shocks on asset prices could be undermined by mis-measurement of these shocks.[1]

In this paper we show that, to study the effect of IST shocks on asset prices, one does not need to construct proxies for IST shocks. Exploiting the economic mechanism through which technical change gets embodied into new capital stock, we propose a new, proxy-free, methodology for measuring the exposure of a firm's stock return to IST shocks. Our methodology rests on the observation that IST shocks, by definition, *must* affect a firm's value through investment expenditures. Therefore the exposure of a firm's return to IST shocks can be measured by its investment expenditures *relative* to its market value. After developing the theoretical foundations of this "investment-based" approach, we apply the methodology to study the role of these shocks in explaining the value premium, i.e., the tendency of value stocks to earn higher expected returns than growth stocks.

A simple example illustrates the key intuition behind our investment-based measure of IST risk exposure. Consider a firm with a market value of $P = \$100$ that plans to invest $I = \$20$ of capital. Suppose that the occurrence of a transitory IST shock $\varepsilon = 1\%$ decreases the unit price of capital from \$1 to \$0.99. As a result, the firm value increases

[1] Garlappi and Song (2014) find that the correlation between two commonly used IST proxies—the change in the relative price of equipment and the return spread between investment and consumption goods producers—is only 0.04 in the 1930–2012 period and 0.02 in the more recent 1963–2012 period.

by the current saving in the investment cost, i.e., $I \times \varepsilon = 20 \times 0.01 = \$0.2$, which implies a return $R = (I \times \varepsilon)/P = 0.2/100 = 0.2\%$. The firm's beta with respect to IST shocks is the percentage change in firm value for one percent change in IST, i.e., $\beta^{\text{IST}} = R/\varepsilon$, which, by the definition of the return R, corresponds to the firm's investment-to-price ratio, $I/P = 0.2$. In the paper we show that this intuition generalizes to a multi-period setting in which the effects of IST shocks are persistent, and show that a firm's IST beta is the sum of discounted future investment expenditures scaled by the firm's current market capitalization. Because investment expenditures are ex-post observable, we can estimate IST betas *directly* from investment data thus avoiding the need to use noisy proxies of IST shocks.

We use our methodology to study the relationship between IST shocks and the value premium. To this purpose, we estimate investment-based IST betas of book-to-market portfolios using a sample of U.S. listed common stocks covering the period 1963–2012. We find that value firms exhibit *higher* investment-based IST betas than growth firms. This pattern is in stark contrast with that of proxy-based IST betas. In fact, using two commonly used proxies for IST shocks to construct IST betas—the change in the relative price of equipment and software from the NIPA tables and the return spread between investment and consumption good producers—we find that, consistent with the existing literature, value firms exhibit *lower* proxy-based IST betas than growth firms.

The empirical evidence on the investment-based IST betas across book-to-market portfolios is important because it imposes novel restrictions that can be useful in identifying the economic mechanism through which IST shocks may affect prices. We investigate such restrictions within the theoretical framework developed by Kogan and Papanikolaou (2013, 2014) (KP hereafter). Within this framework a firm's "true" IST beta is equal to the fraction of growth opportunities in the firm's total value. A comparison with this true IST beta provides therefore a natural way to assess the validity of our proposed measure of IST beta.

We first show that, within KP's framework, a firm's investment-based and proxy-based IST betas are theoretically equivalent to the true IST beta. However, unlike investment-based IST betas, proxy-based betas are typically dependent on specific structural assumption within a model, making them more vulnerable to potential model misspecification. If the model is misspecified, one can still estimate the true IST beta using the investment-based approach, but not the proxy-based approach. This may explain why the betas from the two approaches are different in the data. We then show that, in the model, when cross-sectional variation in book-to-market is driven primarily by variation in growth opportunities, value firms have a *lower* exposure to IST shocks as it is commonly assumed in the existing literature. However, when cross-sectional variation in book-to-market is driven primarily by variation in the value of assets in place, value firms have a *higher* exposure to IST shocks. These findings have potential implications for the risk premium of IST shocks. In fact, assuming that IST shocks help explain the positive value premium in the data, IST betas that are decreasing in book-to-market imply a *negative* IST risk premium. On the contrary, IST betas that are increasing in book-to-market imply a *positive* IST risk premium. The empirical fact that investment-based IST betas are increasing in book-to-market lends support to the case of a positive IST risk premium. This evidence imposes an important restriction on general equilibrium asset pricing models with capital embodied shocks.

Our main idea of using firms' investment to study the cross section of returns closely relates to the large investment-based asset pricing literature that emphasizes the link between investment and stock returns within a neoclassical Q-theory framework (Hayashi (1982)). This literature explores the role of firms' optimal investment decisions in the determination of expected stock returns—see, e.g., Cochrane (1991, 1996), and, more recently, Liu, Whited, and Zhang (2009) and Lin and Zhang (2013). We follow the same general idea of this literature and focus on the link between firms' investment and their exposure to capital-embodied technical change.

Our paper also relates to a vast literature, pioneered by Berk, Green, and Naik (1999), that uses structural models of heterogeneity in firms' investment decisions to study the cross section of returns. Significant contributions include Gomes, Kogan, and Zhang (2003), Carlson, Fisher, and Giammarino (2004), Zhang (2005). Recent studies that introduce sources of risk in addition to neutral productivity shocks include Garleanu, Kogan, and Panageas (2012) and Garleanu, Panageas, and Yu (2012). Our paper complements this literature by studying the role of IST shocks in explaining cross-sectional return patterns, such as the value premium.

A growing literature in macroeconomics and finance studies the effect of IST shocks on growth, business cycles, and asset prices. Greenwood, Hercowitz, and Krusell (1997, 2000) and Fisher (2006) show that IST shocks can account for a large fraction of growth and variations in output and Justiniano, Primiceri, and Tambalotti (2010) emphasize the importance of IST shocks for business cycles. Christiano and Fisher (2003) study the implications of IST shocks for aggregate asset prices. Papanikolaou (2011) introduces IST shocks in a two-sector general equilibrium model. Garlappi and Song (2015) emphasize the importance of capital utilization flexibility and product market competition in determining the equilibrium effects of IST shocks on asset prices. We differ from these papers by focusing on the cross-sectional asset pricing implication of IST shocks.

Finally, our paper also relates to more recent studies that investigate the pricing impact of IST shocks on cross-sectional asset returns. Kogan and Papanikolaou (2013, 2014) explore how IST shocks can explain return patterns in the cross-section that are associated with firm characteristics. Li (2013) proposes a rational explanation of the momentum effect in the cross-section by using investment shocks. Yang (2013) uses investment shocks to explain the commodity basis spread. Garlappi and Song (2014) use proxy-based measures of firms' IST exposure to assess the ability of IST shocks to explain the magnitude of the value premium and momentum profits in the U.S. stock market. We complement this literature by providing a new, investment-based, methodology to estimate the IST risk exposure and analyze its effect on the cross section of equity returns.

Our paper makes three contributions to the asset pricing literature. First, we provide a new, theoretically motivated, methodology to study the effect of IST shocks on asset prices that does not require the use of potentially misspecified proxies of IST shocks. Second, we provide new, independent, evidence on the relative risk exposures to IST shocks for book-to-market portfolios. Finally, we show how our new methodology can be used to differentiate among different economic mechanisms available in the existing literature. By combining theoretical analysis with empirical evidence, our study complements the existing investment-based asset pricing literature and offers a new channel, i.e., a firm's exposures to investment shocks, to understand the relationship between investment and expected returns in the cross-section.

The rest of the paper is organized as follows. Section 2 illustrates the general idea behind our investment-based approach to IST betas. Section 3 documents the empirical evidence of IST betas for book-to-market portfolios. Section 4 studies IST betas for book-to-market portfolios within the structural model of Kogan and Papanikolaou (2014). Section 5 provides a discussion of the results and Section 6 concludes.

2 Investment-based IST exposure: the general idea

A firm's investment expenditures can be used to measure directly the exposure of its' stock return to IST shocks. In this section we illustrate the main intuition behind this claim.

Let us consider an infinitely-lived firm that produces output through a declining-return-to-scale technology requiring physical capital as the only input. In each period the firm decides whether to incur investment expenditures in order to increase capital. The firm value is the present value of future net cash flows, i.e., output net of investment expenditures. The price of new capital is subject to exogenous shocks, which we refer to as IST shocks. We assume that such shocks have a direct impact *only* on the cost of new capital but not on the valuation of the capital already installed. Implicitly this means that we ignore the general equilibrium effects of IST shocks on the discount rate used to evaluate future cash flows. We discuss below the implications of this assumption.

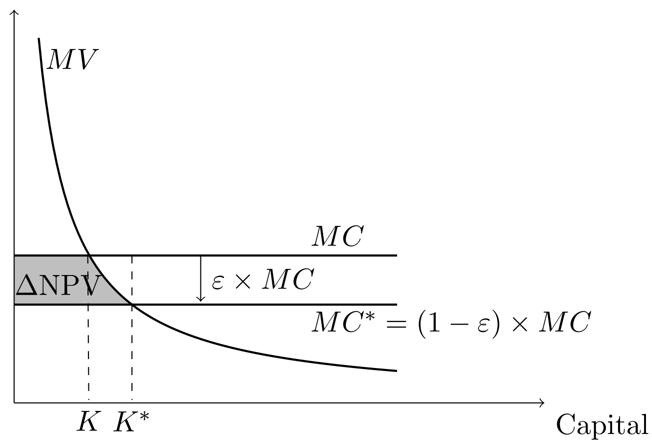

Figure 1: IST shocks and investment expenditures: a graphical illustration.

Figure 1 provides a graphical illustration of the proposed measure of a firm's exposure to an IST shock. In the figure we consider a firm's optimal choice of physical capital. The declining curve MV represents the marginal value of capital. The horizontal line MC represents the marginal cost of investment, i.e., the price of new capital, which, for simplicity, we take as a constant.[2] Let us consider an IST shock ε to the price of capital. Under our assumption, a positive IST shock ε causes a drop in the marginal cost of capital from MC to $MC^* = (1-\varepsilon) \times MC$ but does not affect the marginal value of capital MV.

As a consequence of the shock ε, the firm will "save" on investment costs, and hence increase its NPV by an amount represented by the shaded area in Figure 1, which is approximately equal to

$$\Delta NPV^* \approx \varepsilon \times MC \times K^* \approx \varepsilon \times MC^* \times K^* = \varepsilon \times I^*, \tag{1}$$

[2] The main intuition is unaffected by considering an increasing marginal cost function as in the case of convex capital adjustment costs.

where we ignore terms of order ε^2 and use the fact that investment expenditure $I^* = MC^* \times K^*$.[3] Hence, *per unit of shock* ε the NPV increases "on impact" by an amount I^* and this positively affects the firm's value. If the IST shock is persistent, it impacts not only the current period but also all future investment costs. Therefore, the effect of an IST shock at time t on firm value can be written approximately as follows

$$\Delta P_t \equiv P_t - P_{t-1} \approx \varepsilon \times PV_t \left(\sum_{s=0}^{\infty} I^*_{t+s} \right), \tag{2}$$

where P_t is the firm's market value at time t, I^*_{t+s} is the investment expenditure at time $t+s$, and $PV_t(\cdot)$ denotes present value at time t.[4] The firm's return beta on the IST shock can be written as

$$\beta_t^{\text{IST}} = \frac{\Delta P_t / P_{t-1}}{\epsilon} \approx \frac{PV_t \left(\sum_{s=0}^{\infty} I^*_{t+s} \right)}{P_{t-1}}. \tag{3}$$

Equation (3) illustrates that, in this simple framework, investment expenditures are directly related to a firm's return sensitivity to IST shock. The expression for β_t^{IST} is intuitive: a persistent per-unit positive IST shock decreases all future investment cost, and therefore increases firm value by the discounted future investment expenditures, i.e., $PV_t \left(\sum_{s=0}^{\infty} I^*_{t+s} \right)$. The increase in firm value scaled by lagged firm value, P_{t-1}, represents the response of the firm's return to the IST shock, i.e., its IST beta.

In a more general setting with homogeneous capital, the analysis above will still be valid after interpreting K^* as the *change* in the level of installed capital. In this setting, the curve MV in Figure 1 represents Tobin's marginal Q (see Hayashi (1982)) and, in the presence of convex adjustment costs, the curve MC would be increasing in K. The total investment expenditure equals the required physical capital (including a potential

[3] Alternatively, we could have used the approximation $\Delta NPV \approx \varepsilon \times MC \times K = \varepsilon \times I$, with $I = MC \times K$. Because $K^* - K$ is of order ε, the difference between ΔNPV and ΔNPV^* is of order ε^2. Note, however, that empirically we observe only the investment response to the IST shock, I^*, but not I.

[4] In Section 4 we provide an explicit characterization of the present value $PV_t(\cdot)$ in the context of a structural model of investment characterized by non-stationary aggregate neutral and capital embodied shocks, and transitory idiosyncratic profitability shocks.

adjustment cost) multiplied by the per-unit price of capital goods. Since IST shocks affect only the *per-unit price* of capital, a shock of, say, 1% to the price of capital good implies a 1% change in the total investment expenditures, all else being equal. Therefore, even in the case of convex adjustment costs, the effect of an IST shock on firm's value is proportional to the firm's investment expenditures and hence equation (3) still holds.

It is important to emphasize that (3) applies quite generally in a partial equilibrium setting. The only assumption needed for this claim is that the marginal value of capital MV is unaffected by the IST shock. To see why (3) is a robust result, note that the analysis above captures the *marginal* effect of IST shock, even in the presence of other, unmodeled, shocks. For example, a demand shock that affects marginal cost (MC) and marginal value of capital (MV) will obviously impact the chosen level of K in Figure 1. However, even in this case, the sensitivity of a firm's value to IST shocks is still given by (3), for which observing investment expenditure (and not the demand shock itself) is sufficient.

If the IST shock has general equilibrium effects on the discount rate, then the marginal value MV in Figure 1 will also be affected by the shock ε, implying that equation (3) may no longer hold. A general equilibrium analysis can only be performed by committing to a specific structure of preferences and technology, and is therefore sensitive to these specific choices (see, e.g., Papanikolaou (2011) and Garlappi and Song (2015)). Given the cross-sectional focus of our study, we believe that a partial equilibrium approach is a worthwhile exercise that, as we show in Section 4, complements and extends similar existing work that relies on proxy-based measures of IST exposure.

3 IST exposures of book-to-market portfolios: empirical evidence

In this section, we empirically analyze the exposure of book-to-market portfolios to IST shocks. Section 3.1 constructs empirical measures of investment-based IST betas for book-to-market portfolios and Section 3.2 estimates IST betas from commonly used proxies of IST shocks.

3.1 Investment-based IST betas

We consider all U.S. common stocks (with share code of 10 or 11) from 1963 to 2012. The price and return data are from CRSP, and accounting data are from Compustat. Because our focus is on firms' investment in capital goods, we exclude financial stocks, i.e., firms with Standard Industry Classification (SIC) codes between 6000 and 6999. We first sort firms according to their book-to-market ratio at the end of each year and then hold the portfolio for the following year.[5]

To construct an empirical measure of IST beta, we implement equation (3) under the following three assumptions. First, we use a constant discount rate η when computing the present values of future investment, i.e.,

$$PV_t\left(\sum_{s=0}^{\infty} I_{ft+s}\right) = \mathbb{E}_t\left[\sum_{s=0}^{\infty}\frac{I_{ft+s}}{(1+\eta)^s}\right]. \tag{4}$$

Second, we assume that ex-post realizations of investment expenditures provide a good approximation for their expected value. Specifically, we assume that

$$\mathbb{E}_t\left[\sum_{s=0}^{\infty}\frac{I_{ft+s}}{(1+\eta)^s}\right] \approx \sum_{s=0}^{\infty}\frac{I_{ft+s}}{(1+\eta)^s}. \tag{5}$$

This is a reasonable assumption given our focus on portfolios rather than individual firms. Third, due to data limitation, we track firms' investment expenditures for ten years after

[5] To calculate the book-to-market ratio, we use a firm's book equity for the fiscal year end (as in Fama and French (2008a,b)) and its market capitalization (price×share outstanding) at the end of December of year t. If Compustat book equity is missing, we use the historical book equity as in Davis, Fama, and French (2000), available from Ken French's website.

portfolio formation. That is, we approximate equation (3) by

$$\beta^{\mathrm{IST}}_{10,t} = \sum_{s=0}^{9} \frac{1}{(1+\eta)^s} \frac{I_{t+s}}{P_{t-1}}, \tag{6}$$

where the subscript '10' indicates that we take the sum of ten years of discounted investment expenditures scaled by the current market value as a measure of IST beta.

In (6) the discount rate η is the only free parameter. We take a value of $\eta = 10\%$ in our benchmark analysis and assess the robustness of our findings under different values of η. We will show that equation (6) provides a good approximation of the true IST beta in the theoretical model of Section 4.

To construct the portfolio-level IST betas according to equation (6), we use firm-level capital expenditures ($CAPX$) from COMPUSTAT, as a measure of investment (I), and market capitalization from CRSP, as a measure of market value (P). Following (6), we construct the portfolio-level IST betas by taking the average firm-level I_{t+s}/P_{t-1} ratios and adding these ratios over ten years.[6] The use of value-weighted averages in the construction of IST betas effectively assumes that firms with missing capital expenditures are treated as the average of the firms with valid capital expenditures data. We explore alternative ways to dealing with delisting of firms later in this section.

Table 1 summarizes the returns, investment rates, and IST betas for book-to-market portfolios. Panel A reports the book-to-market portfolios' returns in excess of risk-free rate and investment rates. The excess return pattern confirms the existence of a positive value premium. The return difference for the high-minus-low book-to-market portfolio is 6.76% per year (with a t-value of 2.56). The difference in the investment rate between high and low book-to-market portfolios is -21%. The investment-based IST betas ($\beta^{\mathrm{IST}}_{10}$), reported in Panel B, are monotonically increasing in book-to-market ratio: $\beta^{\mathrm{IST}}_{10}$ increases from 0.50 for the growth firms to 2.94 for the value firms, with a beta difference of 2.44

[6] For example, the I_t/P_{t-1} ratio of portfolio i in year t is calculated as the value-weighted average $\sum_{f\in\mathcal{F}^i} w_{f,t-1} I_{f,t}/P_{f,t-1}$ where $I_{f,t}/P_{f,t-1}$ is firm f's I/P ratio, $w_{f,t-1} = P_{f,t-1}/\sum_f P_{f,t-1}$ are the weights, and $\mathcal{F}^i$ is the set of firms in portfolio i with a non-missing I/P ratio.

(with a t-value of 6.42) for the high-minus-low (HML) portfolio. If we approximate IST betas by $\beta_{10}^{\mathrm{IST}}$, a relatively small IST premium of 2.5% can generate a sizable value premium of $2.44 \times 2.5\% = 6.10\%$. Therefore, investment data indicate that IST shocks have the potential to generate a large value premium if the IST risk premium is positive.

To assess the robustness of the results reported above, we consider two modifications to our procedure for estimating investment-based IST betas.[7] The first modification concerns the discount rate η used in equation (6). Besides the benchmark value $\eta = 10\%$, we consider a lower value of 5% and a higher value of 15%. We find that a different discount rate affects only the magnitude, but not the sign, of the IST beta spread between the high and the low book-to-market portfolios.

The second modification allows for the possibility that not all capital expenditures are affected by IST shocks. This can happen, for example, when firms need to replace parts of an aging equipment, and the price for replacements is not directly affected by the price of state-of-the-art technology. To address this possibility, we take an approach similar to that followed in modelling depreciation of physical capital and assume that a fixed fraction θ of a firm's installed capital K_{t-1} needs to be replaced, and that this replacement cost is not directly affected by the IST shocks.[8] Therefore, at each time t the adjusted capital expenditures, $\hat{I}_t$, that are affected by the IST shocks, are determined by

$$\hat{I}_t = \max\{0, I_t - \theta K_{t-1}\}. \tag{7}$$

Given that capital expenditures are non-negative ($I_t \geq 0$), it follows that $\hat{I}_t = I_t$ when $\theta = 0$, which is the case considered in the previous analysis. For robustness, we consider an alternative value for the depreciation parameter $\theta = 10\%$, which is relatively high compared to commonly used values of a firm's capital depreciation rate.[9]

[7]In unreported analysis, we also confirm that our results are unaffected if we restrict our sample to non-financial firms that produce consumption goods.

[8]The physical capital (K) is measured by net Property, Plant and Equipment ($PPEN$) from Compustat.

[9]If, alternatively, we assume that a fixed fraction θ of the investment expenditures I_t, (instead of capital K_{t-1}) is not affected by IST shocks, then $\hat{I}_t = (1 - \theta)I_t$ and all the results with $\theta = 0$ will be essentially unaffected.

Figure 2 plots the investment-based IST betas (β_{10}^{IST}) for each book-to-market portfolio across different parameter values. The IST betas increase monotonically with book-to-market and decrease with both θ and η. The high-minus-low difference in the betas ranges from 0.78 to 3.01 and is statistically significant (with t-values higher than 4.47) across all parameter values.

In the above analysis, we calculate portfolio-level IST betas based on capital expenditures for a 10-year window after portfolio formation (see equation (6)). This approach can have two potential problems. First, truncating the time series of investment after 10 years can underestimate IST betas. This is a valid concern if one were interested in measuring the level of IST betas. However, because of our focus on the cross section, we are concerned more with the relative raking than the actual level of betas. In our analysis, we find that the differences in the investment-to-price ratio (I_{t+s}/P_{t-1}) across book-to-market portfolios are fairly persistent over time. Therefore, we do not expect any qualitative change in the IST beta rankings across the book-to-market portfolios from using a longer time series of investment expenditures.

Second, some firms may be delisted over time and this can bias our measure of IST betas. In calculating portfolio-level IST betas, we assume that delisted firms have the same average capital-expenditure-to-price ratio as the surviving firms. Since delisted firms are more likely to make less investment than the average firm, our implementation may overestimate the level of investment expenditures. As a robustness check, we repeat our analysis under the assumption that delisted firms make zero capital expenditure, which underestimates the level of investment expenditure.[10] Under this alternative way of handling delisting, we find that IST betas are qualitatively similar to those reported in Figure 2.

In summary, based on the evidence from investment expenditures reported in this section, the IST beta spread between value and growth is *positive*. This result is robust to a wide range of parameter values.

[10]To implement this case, we use total portfolio-level investment expenditures divided by the portfolio's total market capitalization, effectively assuming that delisted firms have zero investment expenditures.

3.2 Proxy-based IST betas

In this section we compare investment-based IST betas of book-to-market portfolios to the corresponding proxy-based quantities. To construct proxy-based IST betas we focus on two IST proxies commonly used by existing studies: one based on macroeconomic data and the other based on financial market data.[11] The first measure of IST shock ($Ishock$), originally proposed by Greenwood, Hercowitz, and Krusell (1997), is defined as:

$$Ishock_t = -\left[\ln\left(p^I/p^C\right)_t - \ln\left(p^I/p^C\right)_{t-1}\right], \tag{8}$$

where p^I is the price deflator for equipment and software in gross private domestic investment, and p^C is the price deflator for nondurable consumption goods. The price deflator for nondurable consumption goods, p^C, is from the National Income and Product Accounts (NIPA) tables. The price deflator of investment goods, p^I, is obtained from the quality-adjusted series of Israelsen (2010).[12] A positive technology innovation reduces the relative price of new capital goods and results in a positive measure of $Ishock$.

The second measure of IST shocks (IMC), originally proposed by Papanikolaou (2011), is the stock return spread between investment and consumption producers, i.e.,

$$IMC_t = R_t^I - R_t^C, \tag{9}$$

where R_t^I and R_t^C are the returns on a portfolio of firms producing, respectively, the investment and consumption goods. In determining whether a firm belongs to the investment or consumption sectors, we follow the procedure of Gomes, Kogan, and Yogo (2009) who assign each Standard Industry Classification (SIC) code to either the investment or consumption sectors on the basis of the 1987 benchmark Input-Output tables. A positive investment shock benefits investment firms relatively more and therefore results in a positive measure of IMC.

[11] Other measures proposed in the literature include the change in the aggregate investment to consumption ratio, and Fama and French's (1993) HML portfolio. See, e.g., Kogan and Papanikolaou (2014).

[12] We are grateful to Ryan Israelsen for sharing with us the annual series of quality-adjusted equipment prices.

To estimate the proxy-based IST beta of a given portfolio, we regress the time series of the portfolio excess returns on an IST proxy. We consider both univariate and bivariate time-series regressions. In univariate regressions, we use the IST proxy as the only regressor. In bivariate regressions, in addition to the IST proxy, we consider either the return on the market portfolio (MKT) or the growth rate in total-factor-productivity (TFP).[13] We repeat the estimation for all book-to-market portfolios and compute the beta spreads for value-minus-growth.

Panel C of Table 1 reports the estimates of proxy-based IST betas for book-to-market portfolios. In univariate regression, $Ishock$ betas are negative for all portfolios, with most estimates statistically significant. The beta difference for HML is -0.93 (with a t-value of -0.97). The univariate IMC betas are all positive with most estimates statistically significant. The beta difference for HML is -0.05 (with a t-value of -0.24). Bivariate regressions give similar patterns of IST betas. For example, controlling for the market factor (MKT), although $Ishock$ and IMC betas are different from their univariate counterparts, their high-minus-low spread is similar to that observed in the univariate case. In bivariate regressions that control for TFP growth, the values of univariate and bivariate betas are very close.

These results indicate that proxy-based IST betas of value firms are *lower* than those of growth firms. This is in contrast to the earlier finding that investment-based betas of value firms are *higher* than those of growth firms.

4 IST exposures of book-to-market portfolios: a structural model

To understand the discrepancy between proxy-based and investment-based IST betas documented in the above empirical analysis, we analyze the implication of these two dif-

[13]The annual TFP is the multifactor productivity measure for private business sector from the Bureau of Labor Statistics.

ferent measures within a structural model of investment. To this purpose, we derive our proposed investment-based IST beta within the theoretical framework of Kogan and Papanikolaou (2013, 2014).[14] In Section 4.1 we summarize the model setup and in Section 4.2 we provide a closed-form expression for the investment-based IST beta. We compare the investment-based IST betas with the proxy-based IST betas in Section 4.3 and provide numerical simulations of book-to-market portfolios within the model in Section 4.4.

4.1 Model setup

There is a continuum $\mathcal{F}$ of measure one of infinitely lived firms who behave competitively in the product market but have monopoly access to their growth opportunities. At time t, each firm $f \in \mathcal{F}$ owns a finite number $\mathcal{J}_t^f$ of existing projects. Project j, owned by firm f, produces a flow of output equal to

$$y_{fjt} = \varepsilon_{ft} u_{jt} x_t K_j^{\alpha}, \tag{10}$$

where ε_{ft} a firm-specific productivity shock; u_{jt} is a project-specific productivity shock; x_t is the common productivity shock for all existing projects; K_j is the project's physical capital which is determined at the time of the project's initial investment; and, $\alpha \in (0, 1)$ captures decreasing returns to scale at the project level. Each project expires independently at a Poisson death rate δ.

The evolution of the three shocks is governed by the following processes:

$$\begin{aligned} d\varepsilon_{ft} &= -\theta_{\varepsilon}(\varepsilon_{ft} - 1)dt + \sigma_{\varepsilon}\sqrt{\varepsilon_{ft}}dB_{ft}, & (11) \\ du_{jt} &= -\theta_u(u_{jt} - 1)dt + \sigma_u\sqrt{u_{jt}}dB_{jt}, & (12) \\ dx_t &= \mu_x x_t dt + \sigma_x x_t dB_{xt}, & (13) \end{aligned}$$

[14] The modelling framework in Kogan and Papanikolaou (2013) is similar to that in Kogan and Papanikolaou (2014) with two main differences. First, Kogan and Papanikolaou (2013) do not consider firm-specific idiosyncratic shocks. The absence of firm-specific shocks weakens the relationship between profitability and investment opportunities. Second, Kogan and Papanikolaou (2013) introduce uncertainty about the firm's growth opportunities, which can be learned from a public signal. This learning feature helps to link growth opportunities to idiosyncratic volatility.

where dB_{ft}, dB_{jt}, and dB_{xt} are increments of independent standard Brownian motions.

At each time t, firm f acquires new projects according to a firm-specific Poisson process with arrival rate

$$\lambda_{ft} = \lambda_f \cdot \tilde{\lambda}_{ft}, \tag{14}$$

where λ_f is a firm-specific constant and $\tilde{\lambda}_{ft}$ follow a two-state continuous time Markov-chain with states $\lambda_H > \lambda_L$ and transition probability

$$P = \begin{pmatrix} 1 - \mu_L dt & \mu_L dt \\ \mu_H dt & 1 - \mu_H dt \end{pmatrix}. \tag{15}$$

The state $\lambda_{ft} = \lambda_f \cdot \lambda_H$ is the *high growth* state and the $\lambda_{ft} = \lambda_f \cdot \lambda_L$ is the *low growth* state. The quantities $\mu_H dt$ and $\mu_L dt$ denote the instantaneous probabilities of transitioning, respectively, into a high or low growth state. Without loss of generality, $\mathbb{E}[\tilde{\lambda}_{ft}] = 1$. Upon arrival of a new project j, the firm makes a take-it-or-leave-it decision. If the firm takes the project, it chooses the associated size of capital K_j and pays the corresponding investment expenditure of

$$i(x_t, z_t, K_j) = \frac{x_t}{z_t} K_j, \tag{16}$$

which depends on productivity, x_t, size of the new capital, K_j, and on the embodied *IST shock*, z_t. A positive realization of z_t reduces the cost of new capital investment. The process for IST shocks z_t also follows a geometric Brownian motion

$$dz_t = \mu_z z_t dt + \sigma_z z_t dB_{zt}, \tag{17}$$

with dB_{zt} a standard Brownian motion independent of dB_{ft}, dB_{jt}, and dB_{xt}. When a firm invests in a project j, the project specific productivity is set to its long run value $u_{jt} = 1$.

The stochastic discount factor π_t is given by

$$\frac{d\pi_t}{\pi_t} = -r dt - \gamma_x dB_{xt} - \gamma_z dB_{zt}, \tag{18}$$

where r is the constant risk-free rate, and γ_x and γ_z are the constant prices of risk for x_t and z_t, respectively.

Kogan and Papanikolaou (2014) show that the value of assets in place (VAP) and the present value of growth opportunities (PVGO) for firm f are given, respectively, by

$$\mathrm{VAP}_{ft} = x_t \sum_{j \in \mathcal{J}_t^f} A(\varepsilon_{ft}, u_{jt}) K_j^{\alpha}, \tag{19}$$

$$\mathrm{PVGO}_{ft} = x_t \, z_t^{\frac{\alpha}{1-\alpha}} G(\varepsilon_{ft}, \lambda_{ft}), \tag{20}$$

where $A(\varepsilon_{ft}, u_{jt})$ and $G(\varepsilon_{ft}, \lambda_{ft})$ are defined in equations (A.2) and (A.5) of Appendix A. The firm value is the sum of the two components,

$$P_{ft} = \mathrm{VAP}_{ft} + \mathrm{PVGO}_{ft}. \tag{21}$$

Using (21), the firm's return IST exposure is given by

$$\beta_{ft}^{z} = \frac{\partial \ln P_{ft}}{\partial \ln z_t} = \frac{\alpha}{1-\alpha} \frac{\mathrm{PVGO}_{ft}}{P_{ft}}. \tag{22}$$

A firm's return exposure to IST shock is therefore proportional to the relative fraction of growth opportunities in the firm's total value. Unfortunately, because the fraction of growth opportunities in the firm value is not directly observable, in order to apply the above framework empirically, it is important to find an operational way to measure a firm's IST exposure.

4.2 Investment-based IST beta

In this subsection we show that the intuition of Section 2 allows us to derive an expression of a firm's IST beta equivalent to (22) that, similar to equation (3), depends on the path of its future investment expenditures. To see this note that, because the arrival rate of new projects is exogenous, firms' investment decision follows a simple intra-temporal NPV rule. That is, at each time t firm f maximizes the project j's NPV:

$$\text{NPV}_{jt} = v(\varepsilon_{ft}, 1, x_t, K_j) - i(x_t, z_t, K_j). \tag{23}$$

where

$$v(\varepsilon_{ft}, u_{jt}, x_t, K_j) = \mathbb{E}_t\left[\int_t^{\infty} e^{-\delta(s-t)}\frac{\pi_s}{\pi_t}\varepsilon_{fs}u_{js}x_sK_j^{\alpha}ds\right] = A(\varepsilon_{ft}, u_{jt})x_tK_j^{\alpha}, \tag{24}$$

with $A(\varepsilon_{ft}, u_{jt})$ defined in equation (A.2) of Appendix A. The optimal capital choice that maximizes the NPV (23) is then given by

$$K_t^* = (\alpha z_t A(\varepsilon_{ft}, 1))^{\frac{1}{1-\alpha}}. \tag{25}$$

The following proposition formalizes how a firm IST beta depends on investment expenditures.

Proposition 1. *Under the assumption of the structural model described in Section 4.1, firm f's stock return IST beta is given by*

$$\beta_{ft}^z = \frac{\mathbb{E}_t\left[\int_t^{\infty} e^{-\eta(s-t)}I_{fs}ds\right]}{P_{ft}}, \tag{26}$$

where $\eta = r + \gamma_x\sigma_x + \frac{\alpha}{1-\alpha}\gamma_z\sigma_z$, I_{fs} is firm f's investment expenditures at time s, and P_{ft} is firm f's market value at time t.

Equation (26) is the equivalent of equation (3) derived in Section 2 and follows the same intuition. A positive and persistent IST shock decreases the cost of all future investment expenditures. In response to a positive unit IST shock, the firm value *increases* by the present value of all future investment expenditures. Therefore a firm's IST beta is the present value of future investment expenditures scaled by the current market value. Under this model's structure, the present value in equation (3) is obtained by applying a constant discount rate at all maturities. This lends support to our implementation of investment-based IST beta in equation (6).

4.3 Comparison with proxy-based IST beta

The current model provides a useful setting to compare our investment-based IST beta to a proxy-based measure that relies on financial market data. By assuming the existence of an investment good sector supplying the capital good to the consumption good sector, Kogan and Papanikolaou (2014) show that the return spread between investment and consumption good firms, $IMC = R^I - R^C$, is a mimicking factor for the IST shock.[15] Specifically,

$$\beta_{ft}^{\mathrm{IMC}} \equiv \frac{\mathrm{cov}(R_{ft}, R_t^I - R_t^C)}{\mathrm{var}(R_t^I - R_t^C)} = \frac{1}{\beta_{0t}} \frac{\mathrm{PVGO}_{ft}}{P_{ft}}, \quad \text{where} \quad \beta_{0t} \equiv \frac{\int_{\mathcal{F}} \mathrm{VAP}_{ft} df}{\int_{\mathcal{F}} P_{ft} df}. \tag{27}$$

Equation (27) defines a *proxy-based* measure of IST beta that can be constructed from financial data. Note that, according to equation (22), we can write

$$\beta_{ft}^{\mathrm{IMC}} = \frac{1}{\beta_{0t}} \frac{1-\alpha}{\alpha} \beta_{ft}^{z}, \tag{28}$$

and hence proxy-based IST beta ($\beta_{ft}^{\mathrm{IMC}}$) is an approximation of the investment-based IST beta (β_{ft}^{z}).[16]

Importantly, while it is true that, within the model, the two IST-beta measures are identical, proxy-based measures are more heavily dependent on the model assumptions, hence making them more vulnerable to model misspecification. As discussed in Section 2, our investment-based IST beta rests on considerably fewer structural assumptions.

To see how proxy-based measure depend on structural model assumption, note, for example that a crucial condition for obtaining IMC as a proxy of IST shocks within the model of Section 4.1 is that the value of investment and consumption good producers have the same degree of homogeneity in the neutral productivity shock x_t. Without this

[15] The idea of using IMC as a measure of IST shocks is originally developed in Papanikolaou (2011).

[16] The two are theoretically equivalent, conditional on the realization of the IST shock z_t. To see this, note that, from equations (19)–(21), the term β_{0t} in equation (27) depends on the aggregate IST shock z_t, but not on the neutral productivity shock x_t.

assumption, IMC is *not* a factor-mimicking portfolio for the IST shocks. In Appendix C we show that when output (10) and investment cost (16) have different degree of homogeneity in the neutral shock x_t, the return spread IMC is a mixed measure of both the IST shock z_t *and* the neutral shock x_t.[17]

As we discussed in Section 3.2, another common approach to proxy for IST shocks in the literature is to rely on the relative price of new capital equipment (see equation (8)). In the context of the structural model of Section 4.1, these proxies capture the cost of per-unit capital in consumption units, i.e., x_t/z_t in equation (16). Because it is affected by both neutral (x_t) and investment specific (z_t) shocks, the change in the price of capital cannot uniquely be linked to IST shocks. One potential remedy for this measurement problem is to adjust the capital good price for the effect of productivity shocks, i.e., construct a "quality-adjusted" capital good price, as we did in Section 3.2. However, as for the case of IMC, this adjustment is also model-dependent, and therefore potentially affected by measurement problems.

In summary, because they rely on restrictive modeling assumptions concerning either firms' valuation or the determinants of capital good prices, proxy-based IST betas are a more "fragile" measure of a stock's return exposure to IST shocks than the investment-based measure developed in Section Section 3.1. As we show next, the proposed investment-based approach to measuring a firm's exposure to IST shocks complements the existing proxy-based approach and helps us better understand the channels through which IST shocks may affect firms' return in the cross-section.

4.4 IST betas of book-to-market portfolios

We assess the ability of the structural model of Section 4.1 to generate the empirical pattern of IST beta across book-to-market portfolios documented in Section 3. To this

[17] A similar argument applies to an alternative proxy of IST shocks constructed from the the growth rate difference between the total investment and consumption. Similar to IMC, it can be shown that only under a homogeneity assumption of investment and consumption value with respect to the neutral productivity shock, this proxy is a correct measure of IST shocks.

purpose, we simulate the model under the same parameter values used by Kogan and Papanikolaou (2014) and reported in the column labeled "KP parameters" in Table 2.[18] As in Kogan and Papanikolaou (2014), we simulate the model at a weekly frequency and time-aggregate the information to form annual observations. We simulate 1,000 samples of 2,500 firms over a period of 100 years and drop the first half of each sample to remove dependence on initial values. We report the median across samples of each variable of interest. For example, in each of the 1,000 samples, we form book-to-market portfolios at the end of each year and calculate the portfolio returns for the next year. The sample portfolio average return is the time series average return of each portfolio. We report the median of the average returns across the 1,000 samples.

The results of the simulation for book-to-market portfolios are reported in the left panels of Figure 3. These results confirm the findings of Kogan and Papanikolaou (2014). First, the return is monotonically increasing in book-to-market ratio, consistent with the empirical evidence on the value premium. The average return increases from below 8%, for the lowest book-to-market portfolio, to above 10% for the highest book-to-market portfolio. Second, IST beta is monotonically decreasing in book-to-market ratio. In particular, a constant scaled version of the investment-based IST betas (the dash-dotted line labeled "$5 \times \beta_{10}^{\text{IST}}$") obtained from equation (6) matches well the decreasing pattern of the true IST beta (the solid line labeled "$\beta_{\text{true}}^{\text{IST}}$"). The scale difference is due to the fact that we use only 10 years of investment expenditures to construct the empirical version of the IST beta in (26), and thus we ignore all investment expenditures occurring after 10 years. Given our focus on the cross section of returns, a constant scaling factor in the IST beta will only rescale the magnitude of IST risk premium required to match the return spread, without affecting the interpretation of the economic mechanisms in the model. A similar scaling issue applies to the IMC beta constructed by time series regressions of portfolio returns on the IMC spread, and represented by the starred line in Figure 3. Note

[18]The only difference from the parameters used by Kogan and Papanikolaou (2014) is the distribution of mean project arrival rate λ_f which we take to be uniformly distributed between $[\underline{\lambda}, \overline{\lambda}] = [5, 25]$, as in Kogan and Papanikolaou (2013). Using the non-uniformly distributed λ_f as in Kogan and Papanikolaou (2014) gives the same results.

that β^{IMC} tracks closely the investment-based IST beta β_{10}^{IST} in this model, confirming the equality between these two betas established in equation (28). Finally, consistent with the results reported in Table 1, the growth stocks have much higher investment rate (I/K) than value stocks.

Comparing the investment-based IST betas from the simulation result to those observed in the data and reported in Figure 2, we observe that the model-implied and empirical IST betas have opposite patterns with respect to the book-to-market ratio: in the data, investment-based IST betas are *increasing* across book-to-market portfolios; in this parameterization of the model, investment-based IST betas are *decreasing* across book-to-market portfolios. In the rest of this section we explore alternative parameter values to verify whether the model can replicate the pattern of investment-based IST beta observed in the data. Our goal is simply to assess whether existing models can be made consistent with our new empirical evidence. We would like to stress that it is outside the scope of this paper to propose an alternative calibration of existing models or to claim that the alternative parameterization reported below provides the most accurate explanation of the empirical evidence.[19]

As we show in equation (22), IST beta is determined by the fraction of growth opportunities in firm value ($PVGO/P$). In order to generate IST betas that are increasing in book-to-market ratio within the model, heterogeneity in book-to-market should be driven predominantly by variation in assets-in-place instead of growth opportunities. To see this, let us rewrite the book-to-market ratio as follows

$$B/M = \frac{K}{P} = \frac{K}{VAP} \times \left(1 - \frac{PVGO}{P}\right). \tag{29}$$

[19]The key theoretical implication of the model of Section 4.1 is that the true IST beta is proportional to the fraction of PVGO in the firm value. Note that this implication is a result of the proportionality among project's market value, investment expenditure, and NPV. In the data, this tight relationship may not hold. For example, a firm may invest in a project with near zero NPV, but that requires large investment expenditures. While KP's model setup does not apply to such an example, our investment-based approach developed in Section 2 is independent of the proportionality restrictions and therefore still holds.

If the B/M ratio is driven only by the growth opportunities, that is, if K/VAP is constant in (29), high B/M implies *low* $PVGO/P$. The negative correlation between B/M and $PVGO/P$ is weaker in the presence of shocks that have a relatively large impact on the profitability of existing assets (captured by K/VAP) and a relatively small impact on growth opportunities. To explore these channels, we make three modifications to the above parameterization (see the column labeled "Alternative parameters" in Table 2).

First, we shut down the firm-specific productivity shock ε_f, as in Kogan and Papanikolaou (2013), to reduce the shock to growth opportunities. This is a natural choice because, ε_f is a shock that affects the value of both assets-in-place and growth opportunities.

Second, we reduce the speed of mean-reversion parameter θ_u for the project-specific shock u_j, as in Kogan and Papanikolaou (2013), in order to increase the importance of the project-specific shock within the model. Note that the projet-specific shock will generate a *positive* correlation between B/M ratio and $PVGO/P$. For example, a negative u_j reduces the market value of an existing project, i.e., it decreases VAP but does not affect growth opportunities ($PGVO$). This leads to higher values of both B/M and $PVGO/P$ ratios. A slower mean-reverting parameter for the u_j shock makes its effect stronger because the shocks will last for a longer period.

Finally, we choose a smaller value for the ratio λ_H/λ_L. This ratio represents how many more projects a firm receives when it is in its high growth state relative to its low growth state. From equation (14), firm f's project arrival rate is governed by the Poisson parameter $\lambda_{ft} = \lambda_f \cdot \tilde{\lambda}_{ft}$, where $\tilde{\lambda}_{ft} \in \{\lambda_L, \lambda_H\}$ and $\mathbb{E}[\tilde{\lambda}_{ft}] = 1$. A high ratio λ_H/λ_L implies a wider range for λ_{ft}. Especially in low growth states, the volatility of the Poisson process will dominate the variation in the value of assets in place.[20] In the model of section 4.1 ex-post variation in the number of projects acquired does not affect $PVGO$ while it directly impacts VAP and K. When the Poisson randomness dominates, i.e., when λ_H/λ_L is high, a firm that receives more projects than expected has roughly the same K/VAP

[20]Recall that the mean and variance of a Poisson process with intensity λ, are equal to λ. Hence for low values of λ, the volatility-to-average ratio of the Poisson process, $1/\sqrt{\lambda}$, increases for low values of the arrival rate λ.

as one that receives less projects than expected but it will have a higher VAP and a lower $PVGO/P$ ratio. According to equation (29) firms that receive unexpectedly higher number of projects will then have higher B/M ratios. In other words, the Poisson arrival uncertainty generates a counterfactual positive correlation between B/M and size in the model. This effect is particularly strong in Kogan and Papanikolaou (2014), where the ratio $\lambda_H/\lambda_L = 6.4$. In the alternative parameterization reported in Table 2, we set this ratio to 2, implying that in the high growth state firms receive twice as many projects than in the low growth state. In this alternative parameterization, the effect of Poisson randomness on VAP is weaker, which help reduces the negative correlation between B/M and $PVGO/P$.

We summarize our parameter choice in Table 2, under the column labeled "Alternative parameters". The three right panels in Figure 3 report the results for this alternative parameterization. As the figure illustrates, the pattern of IST beta is *increasing* across book-to-market portfolios, consistent with the empirical evidence reported in Figure 2. Because in this parameterization we use a negative price of risk for the IST shock ($\gamma_z = -0.35$), the model generates a counterfactual *growth* premium. Note that with this alternative parameterization the investment rate (I/K) is also higher for growth stocks than for value stocks.

In summary, the analysis in this section highlights that the investment-based beta we propose represents an important restriction that can help identify the economic mechanisms in a given structural model of investment and returns. Combined with the empirical evidence from the previous section, the main message from our analysis is that, the investment-based evidence indicates that value firms are more exposed to the IST risk than growth firms, and a positive IST risk premium is needed to claim that IST shocks can help explain the value spread observed in the data.

5 Discussion

In Section 4.3 we proved that investment-based and proxy-based betas are theoretically equivalent within the structural model of Kogan and Papanikolaou (2014). However, as shown in the Section 3, the two approaches produce opposite empirical patterns of IST betas for book-to-market portfolios. There are at least two possible reasons for this observed discrepancy. The first reason is that the model does not capture the underlying economic mechanisms that underly the empirical evidence. In this case, we should not expect the equivalence between the two approaches to hold in the data. As illustrated in Section 2, the idea behind our investment-based approach is not dependent on any particular model structure (besides the assumption of declining marginal value of capital), and therefore provides robust estimates of IST betas. The second reason is that, although the model might be capturing the right economic mechanism underlying the data, some of the specific assumptions needed to construct a model-based proxy of IST shock, might not hold in the data. In this case, the resulting proxy-based betas might contain measurement error. In summary, the investment approach provides not only a new, complementary, methodology, but also a useful identifying restriction for cross-sectional asset pricing models, as we demonstrated in the simulations analysis of Section 4.4.

In a related study based on IST proxies, Garlappi and Song (2014) find that the implied risk premium of IST proxies obtained by using only book-to-market portfolios as test assets may not be reliable. In particular, they find that the IST risk premium estimated from proxy-based IST betas on ten book-to-market portfolios changes from negative in the 1963-2012 period, to positive in the early 1930-1962 period or in the full sample spanning from 1930 to 2012. In addition, the IST risk premium is positive and stable over time when estimated from a broader cross-section of assets. This evidence is broadly consistent with the evidence from investment-based IST betas for book-to-market portfolios reported in Section 3.1.

The results of Section 4.4 indicate that a negative IST risk premium fails to match simultaneously the investment expenditures relative to market value and the value premium that we observe in the data. This results raise an important question regarding the sign of the price of risk of IST shocks in equilibrium. Garlappi and Song (2015) point out that an important determinant of the sign of the price of IST risk in equilibrium is the degree of capital utilization. In the context of a two-sector general equilibrium model with consumption and capital good producers they show that, when capital utilization is sufficiently flexible in the economy, the equilibrium price of IST risk is positive, independent of investor's preferences towards the resolution of uncertainty. This is in contrast to general equilibrium models with fixed capital utilizations, such as Papanikolaou (2011), in which the price of IST risk is negative when investors prefer late resolution of uncertainty. We believe that further explorations of the general equilibrium implications of IST shocks for asset prices remains an important venue of future research.

6 Conclusion

In this paper we provide a new methodology for estimating a firm's stock return sensitivity to capital-embodied technology shocks. Our methodology is based on the intuition that a firm's investment contains useful information regarding its exposure to IST shocks. Empirically, we find that investment-based IST betas are higher for value stocks than for growth stocks, contradicting the opposite findings in the existing studies based on IST proxies. To better understand these new empirical findings, we analyze in depth the economic mechanisms of a well-studied structural model of investment. We show that, within this model, our investment-based IST betas provide good estimates of the true IST betas, while proxy-based IST betas are more vulnerable to measurement errors. More importantly, the new evidence provides useful restrictions on the economic mechanisms through which IST shocks affect cross-sectional asset prices.

In light of the discrepancy between investment-based and proxy-based inference, exploring alternative measures of IST shocks to those available in the existing literature is of first-order importance for gaining a better understanding of their effect on asset returns. We believe that the new methodology proposed in this paper represents a useful benchmark to assess the validity of alternative measures of capital-embodied technical change and their effect on asset prices.

A Results from Kogan and Papanikolaou's (2014) model

In this Appendix we reproduce the expressions for the value of assets in place (VAP) and growth options (PVGO) in Kogan and Papanikolaou's (2014) model. Given the stochastic discount factor (18), the market value of an existing project j at time t equals the present discounted cash flows, i.e.,

$$v(\varepsilon_{ft}, u_{jt}, x_t, K_j) = \mathbb{E}_t\left[\int_t^\infty e^{-\delta(s-t)}\frac{\pi_s}{\pi_t}\varepsilon_{fs}u_{js}x_s K_j^\alpha ds\right] = A(\varepsilon_{ft}, u_{jt})x_t K_j^\alpha, \tag{A.1}$$

where

$$\begin{aligned} A(\varepsilon_{ft}, u_{jt}) \quad = \quad & \frac{1}{r+\gamma_x\sigma_x+\delta-\mu_x} + \frac{1}{r+\gamma_x\sigma_x+\delta-\mu_x+\theta_\varepsilon}(\varepsilon_{ft}-1) \\ & + \frac{1}{r+\gamma_x\sigma_x+\delta-\mu_x+\theta_u}(u_{jt}-1) \\ & + \frac{1}{r+\gamma_x\sigma_x+\delta-\mu_x+\theta_\varepsilon+\theta_u}(\varepsilon_{ft}-1)(u_{jt}-1). \end{aligned} \tag{A.2}$$

The value of a firm's assets in place is the market value of its existing projects, i.e.,

$$\text{VAP}_{ft} = \sum_{j\in\mathcal{J}_t^f} v(\varepsilon_{ft}, u_{jt}, x_t, K_j) = x_t \sum_{j\in\mathcal{J}_t^f} A(\varepsilon_{ft}, u_{jt})K_j^\alpha. \tag{A.3}$$

The present value of a firm's growth opportunities at time t, $PVGO_t$, is the discounted NPV of future investments. Proposition 2 in Kogan and Papanikolaou (2014) shows that

$$\text{PVGO}_{ft} = \mathbb{E}_t\left[\int_t^\infty \frac{\pi_s}{\pi_t}\text{NPV}_s^*\lambda_{fs}ds\right] = z_t^{\frac{\alpha}{1-\alpha}}x_t G(\varepsilon_{ft}, \lambda_{ft}), \tag{A.4}$$

where

$$G(\varepsilon_{ft}, \lambda_{ft}) = \begin{cases} \lambda_f\left(G_1(\varepsilon_{ft}) + \frac{\mu_L}{\mu_L+\mu_H}(\lambda_H-\lambda_L)G_2(\varepsilon_{ft})\right), & \tilde{\lambda}_{ft} = \lambda_H \\ \lambda_f\left(G_1(\varepsilon_{ft}) - \frac{\mu_H}{\mu_L+\mu_H}(\lambda_H-\lambda_L)G_2(\varepsilon_{ft})\right), & \tilde{\lambda}_{ft} = \lambda_L, \end{cases} \tag{A.5}$$

and $G_i(\varepsilon)$, $i = 1, 2$, are solutions of the following differential equations:

$$C \cdot A(\varepsilon, 1)^{\frac{1}{1-\alpha}} - \rho_i G_i(\varepsilon) - \theta_\varepsilon(\varepsilon - 1)\frac{d}{d\varepsilon}G_i(\varepsilon) + \frac{1}{2}\sigma_\varepsilon^2 \varepsilon \frac{d^2}{\varepsilon^2}G_i(\varepsilon) = 0, \tag{A.6}$$

with

$$C = \alpha^{\frac{1}{1-\alpha}}(\alpha^{-1} - 1), \tag{A.7}$$

$$\rho_1 = \rho \equiv r + \gamma_x\sigma_x - \mu_x - \frac{\alpha}{1-\alpha}\left(\mu_z - \gamma_z\sigma_z - \frac{1}{2}\sigma_z^2\right) - \frac{1}{2}\left(\frac{\alpha}{1-\alpha}\right)^2 \sigma_z^2, \tag{A.8}$$

$$\rho_2 = \rho + \mu_H + \mu_L. \tag{A.9}$$

B Proof of Proposition 1

Using the optimal investment scale K^* from (25), the investment cost in (16) is

$$i(x_t, z_t, K_t^*) = x_t z_t^{\frac{\alpha}{1-\alpha}}(\alpha A(\varepsilon_{ft}, 1))^{\frac{1}{1-\alpha}}, \tag{B.1}$$

and hence, from (23) we have

$$\mathrm{NPV}_t^* = \frac{C}{\alpha^{\frac{1}{1-\alpha}}} i(x_t, z_t, K_t^*) = \frac{1-\alpha}{\alpha} i(x_t, z_t, K_t^*). \tag{B.2}$$

Direct calculations yield that the present value at time t of firm f's growth opportunities, PVGO_{ft}, is given by:

$$
\begin{aligned}
\text{PVGO}_{ft} &= \mathbb{E}_t\left[\int_t^\infty \frac{\pi_s}{\pi_t}\text{NPV}_s^*\lambda_{fs}ds\right] \\
&= \mathbb{E}_t\left[\int_t^\infty \frac{\pi_s}{\pi_t}\frac{1-\alpha}{\alpha}i(x_s, z_s, K_s^*)\lambda_{fs}ds\right] \\
&= \frac{1-\alpha}{\alpha}\mathbb{E}_t\left[\int_t^\infty \frac{\pi_s}{\pi_t}x_s z_s^{\frac{\alpha}{1-\alpha}}(\alpha A(\varepsilon_{fs},1))^{\frac{1}{1-\alpha}}\lambda_{fs}ds\right] \\
&= \frac{1-\alpha}{\alpha}\int_t^\infty \mathbb{E}_t^{x,z}\left[\frac{\pi_s}{\pi_t}x_s z_s^{\frac{\alpha}{1-\alpha}}\right]\mathbb{E}_t^{\varepsilon,\lambda}\left[(\alpha A(\varepsilon_{fs},1))^{\frac{1}{1-\alpha}}\lambda_{fs}\right]ds \\
&= \frac{1-\alpha}{\alpha}\int_t^\infty e^{\left(-r-\gamma_x\sigma_x-\frac{\alpha}{1-\alpha}\gamma_z\sigma_z\right)(s-t)}\mathbb{E}_t^{x,z}\left[x_s z_s^{\frac{\alpha}{1-\alpha}}\right]\mathbb{E}_t^{\varepsilon,\lambda}\left[(\alpha A(\varepsilon_{fs},1))^{\frac{1}{1-\alpha}}\lambda_{fs}\right]ds \\
&= \frac{1-\alpha}{\alpha}\mathbb{E}_t\left[\int_t^\infty e^{-\eta(s-t)}i(x_s, z_s, K_s^*)\lambda_{fs}ds\right] \\
&= \frac{1-\alpha}{\alpha}\mathbb{E}_t\left[\int_t^\infty e^{-\eta(s-t)}I_{fs}ds\right], \qquad \text{(B.3)}
\end{aligned}
$$

where the first equality is the definition of PVGO_{ft}; the second equality follows from (B.2); the third equality follows from (B.1); the fourth equality uses the fact that the processes x_t and z_t are independent of λ_{ft} and ε_{ft} thus allowing to express the expectation $\mathbb{E}$ as the product of the expectation under the measure governing the dynamics of x_t and z_t, $\mathbb{E}^{x,t}$, and the expectation under the measure governing the dynamics of ε_{ft} and λ_t, $\mathbb{E}^{\varepsilon,\lambda}$;[21] the fifth equality exploits the fact that x_t and z_t are geometric Brownian motions, defined in (13) and (17); the sixth equality follows from the independence of the stochastic processes x_t, z_t, ε_{ft} and λ_{ft}, and uses $\eta \equiv r + \gamma_x\sigma_x + \frac{\alpha}{1-\alpha}\gamma_z\sigma_z$, and the definition of optimal investment in (B.1); and, the last equality follows from the definition of firm-level investment $I_{fs} = i(x_s, z_s, K_s^*)\lambda_{fs}$.

Using (B.3) in the definition of firm f's IST beta (22), we then obtain

$$
\beta_{ft}^z = \frac{\mathbb{E}_t\left[\int_t^\infty e^{-\eta(s-t)}I_{fs}ds\right]}{P_{ft}}. \qquad \text{(B.4)}
$$

[21] If $\text{PVGO}_{ft} < \infty$, by Fubini's Theorem, we can interchange expectation and integration.

■

C IMC spread as a mimicking factor for IST shocks

Let us suppose that output (10) and investment cost (16) are given, respectively by the following two functions

$$y_{fjt} = \varepsilon_{ft} u_{jt} x_t^{\omega_y} K_j^{\alpha}, \quad \text{and} \quad i(x_t, z_t, K_j) = \frac{x_t^{\omega_i}}{z_t} K_j, \quad \omega_y \neq \omega_i. \tag{C.1}$$

Following the same analysis of Section 4.1, it is easy to show that the value of a consumption good firm f is given by

$$\widehat{P}_{ft} = x_t^{\omega_y} \sum_{j \in \mathcal{J}_t^f} \widehat{A}(\varepsilon_{ft}, u_{jt}) K_j^{\alpha} + z_t^{\frac{\alpha}{1-\alpha}} x_t^{\frac{\omega_y - \alpha\omega_i}{1-\alpha}} \widehat{G}(\varepsilon_{ft}, \lambda_{ft}), \tag{C.2}$$

where

$$\widehat{A}(\varepsilon_{ft}, u_{jt}) = \frac{1}{H} + \frac{1}{H+\theta_\varepsilon}(\varepsilon_{ft}-1) + \frac{1}{H+\theta_u}(u_{jt}-1) + \frac{1}{H+\theta_\varepsilon+\theta_u}(\varepsilon_{ft}-1)(u_{jt}-1), \tag{C.3}$$

with $H \equiv r + \omega_y \gamma_x \sigma_x + \frac{1}{2}\omega_y(1-\omega_y)\sigma_x^2 + \delta - \omega_y \mu_x$, and

$$\widehat{G}(\varepsilon_{ft}, \lambda_{ft}) = \begin{cases} \lambda_f \left(\widehat{G}_1(\varepsilon_{ft}) + \frac{\mu_L}{\mu_L+\mu_H}(\lambda_H - \lambda_L)\widehat{G}_2(\varepsilon_{ft}) \right), & \tilde{\lambda}_{ft} = \lambda_H \\ \lambda_f \left(\widehat{G}_1(\varepsilon_{ft}) - \frac{\mu_H}{\mu_L+\mu_H}(\lambda_H - \lambda_L)\widehat{G}_2(\varepsilon_{ft}) \right), & \tilde{\lambda}_{ft} = \lambda_L, \end{cases} \tag{C.4}$$

where $\widehat{G}_i(\varepsilon)$, $i = 1, 2$, are solutions of the following differential equations:

$$C \cdot \widehat{A}(\varepsilon, 1)^{\frac{1}{1-\alpha}} - \hat{\rho}_i \widehat{G}_i(\varepsilon) - \theta_\varepsilon(\varepsilon - 1)\frac{d}{d\varepsilon}\widehat{G}_i(\varepsilon) + \frac{1}{2}\sigma_\varepsilon^2 \varepsilon \frac{d^2}{\varepsilon^2}\widehat{G}_i(\varepsilon) = 0, \tag{C.5}$$

with C given by equation (A.7) and

$$\hat{\rho}_1 = \hat{\rho} \equiv r - \frac{\omega_y - \alpha\omega_i}{1-\alpha}\left(\mu_x - \gamma_x\sigma_x - \frac{1}{2}\sigma_x^2\right) - \frac{1}{2}\left(\frac{\omega_y - \alpha\omega_i}{1-\alpha}\right)^2 \sigma_x^2$$
$$-\frac{\alpha}{1-\alpha}\left(\mu_z - \gamma_z\sigma_z - \frac{1}{2}\sigma_z^2\right) - \frac{1}{2}\left(\frac{\alpha}{1-\alpha}\right)^2 \sigma_z^2, \tag{C.6}$$

$$\hat{\rho}_2 = \hat{\rho} + \mu_H + \mu_L. \tag{C.7}$$

Note that, as $\omega_y, \omega_i \to 1$, $\widehat{P}_{ft} \to P_{ft}$ in (21). The value of investment good producers is

$$\widehat{P}_{It} = \widehat{\Gamma}_t x_t^{\frac{\omega_y - \alpha\omega_i}{1-\alpha}} z_t^{\frac{\alpha}{1-\alpha}}, \quad \text{where} \quad \widehat{\Gamma}_t \equiv \phi\overline{\lambda}_t \alpha^{\frac{1}{1-\alpha}} \hat{\rho}^{-1} \int_{\mathcal{F}} \widehat{A}(\varepsilon_{ft}, 1)^{\frac{1}{1-\alpha}} df, \quad \text{and} \quad \overline{\lambda}_t = \int_{\mathcal{F}} \lambda_{ft} df. \tag{C.8}$$

Comparison of (C.2) and (C.8) shows that, because consumption good firm and investment good firm have different exposures to the productivity shock x_t, the return spread IMC contains information related to both z_t and x_t. Indeed, we can show that the return spread $R_t^I - R_t^C$ is given by

$$R_t^I - R_t^C = \mathbb{E}_t[R_t^I - R_t^C] + \frac{\alpha(\omega_y - \omega_i)}{1-\alpha}\hat{\beta}_{0t}\sigma_x dB_{xt} + \frac{\alpha}{1-\alpha}\hat{\beta}_{0t}\sigma_z dB_{zt}, \tag{C.9}$$

where $\hat{\beta}_{0t} \equiv \left(\int_{\mathcal{F}} \widehat{\mathrm{VAP}}_{ft} df\right) / \left(\int_{\mathcal{F}} \widehat{P}_{ft} df\right)$ and $\widehat{\mathrm{VAP}}_{ft}$ is defined as the first term on the right-hand-side of equation (C.2). Notice that in (C.9) the exposure of the IMC return spread to the x_t shock vanishes only if $\omega_y = \omega_i$. Therefore, a proxy-based IMC beta such as (27) will in general capture a firm's beta with respect to not only the IST shock z_t but also the productivity shock x_t.

In contrast, following the steps for the derivation of equation (B.3) in the proof of Proposition 1, it is straightforward to show that, when consumption and investment good producers have different exposures to the productivity shock, expression (26) for the investment-based beta still holds with a constant discount rate given by $\hat{\eta} = r + (\omega_i + \frac{\omega_y - \omega_i}{1-\alpha})\gamma_x\sigma_x + \frac{\alpha}{1-\alpha}\gamma_z\sigma_z$. This example illustrates the robustness of investment-based IST betas relative to proxy-based IMC betas.

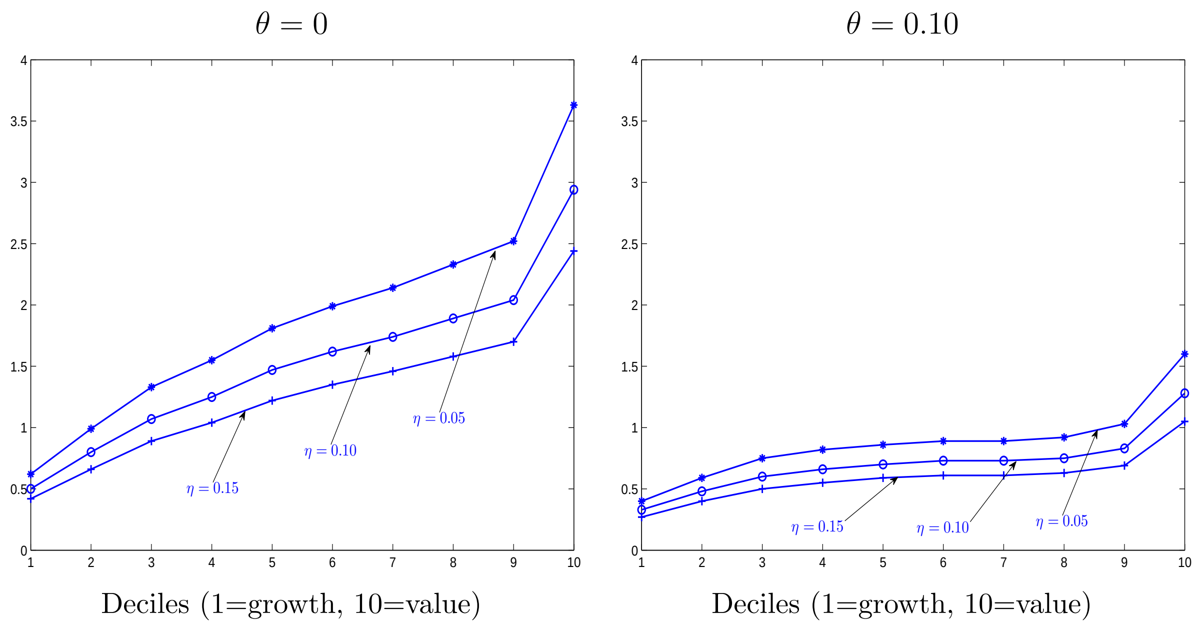

Figure 2: Investment-based IST betas of book-to-market portfolios

The figure reports the investment-based IST betas of book-to-market portfolios estimated from data on U.S. listed common stocks over the period 1963–2012. $\beta_{10}^{\mathrm{IST}}$ is constructed from equation (6) using three different values for η. In constructing $\beta_{10}^{\mathrm{IST}}$, we adjust investment expenditures according to equation (7) with two different values of the parameter θ.

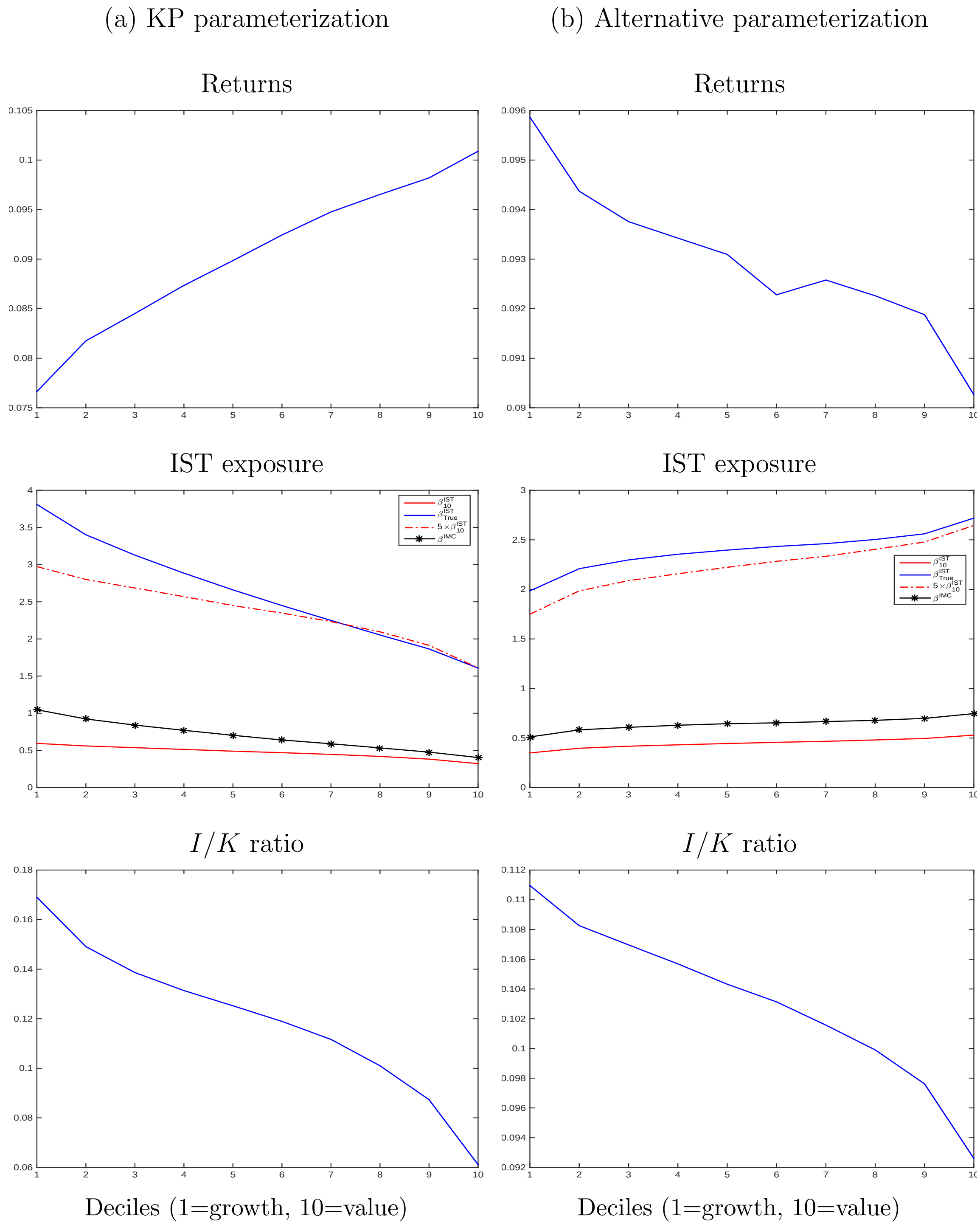

Figure 3: Model implications under alternative parameterizations

The figure reports returns, IST betas, and investment-to-capital (I/K) for 10 book-to-market portfolios obtained from two alternative parameterizations of the structural model of Section 4. The parameter values used in each simulations are reported in Table 2. We simulate 1,000 samples of 2,500 firms over a period of 100 years and drop the first half of each sample to remove dependence on initial values. The figure reports the median numbers across the 1,000 samples.

Table 1: IST betas of book-to-market portfolios

This table reports the excess returns (Ret) and IST exposures for book-to-market portfolios. Panel A reports the portfolio return in excess of risk-free rate and the investment rate (I/K). Panel B reports the investment-based IST betas and panel C reports the proxy-based IST betas. Both the return and the investment rate are calculated using the data one year after the portfolio formation. We use capital expenditure data to estimate the IST exposures β_{10}^{IST} according to equation (6) with $\eta = 0.10$. Investment-based betas are the average across years from 1963 to 2003 (β_{10}^{IST} in 2003 is constructed based on investment from 2003-2012). We use two proxies of IST shocks, $Ishock$ and IMC, to estimate the IST betas. We consider both one-factor and two-factor models, with the second factor to be either the market excess return (MKT) or the total factor of productivity (TFP). The proxy-based beta estimates are based on data from 1963 to 2012. The t-statistics (in parentheses) are Newey-West adjusted with a lag length of 3 years.

	Variable	Low	2	3	4	5	6	7	8	9	High	HML
Panel A: Returns and investment rates												
	Ret (%)	7.01	6.31	7.14	7.53	7.44	8.69	9.27	10.58	10.73	13.77	6.76
		(2.49)	(2.59)	(2.97)	(2.99)	(3.19)	(3.57)	(3.81)	(4.02)	(4.06)	(4.21)	(2.56)
	I/K	0.34	0.27	0.24	0.23	0.20	0.19	0.17	0.15	0.14	0.13	-0.21
Panel B: Investment-based IST betas												
	β_{10}^{IST}	0.50	0.80	1.07	1.25	1.47	1.62	1.74	1.89	2.04	2.94	2.44
		(7.19)	(6.99)	(6.48)	(6.37)	(7.42)	(6.97)	(7.47)	(8.01)	(7.66)	(6.82)	(6.42)
Panel C: Proxy-based IST betas												
IST only:												
	β_{Ishock}	-1.78	-1.74	-1.60	-1.81	-1.25	-1.98	-2.53	-2.82	-2.50	-2.71	-0.93
		(-1.95)	(-2.23)	(-1.92)	(-1.77)	(-1.65)	(-2.13)	(-3.32)	(-2.88)	(-3.04)	(-2.50)	(-0.97)
	β_{IMC}	0.64	0.46	0.55	0.51	0.49	0.59	0.33	0.35	0.39	0.59	-0.05
		(3.04)	(2.56)	(3.38)	(2.91)	(2.57)	(3.70)	(1.57)	(1.60)	(2.01)	(2.43)	(-0.24)
IST+MKT:												
	β_{Ishock}	0.20	0.05	0.16	-0.08	0.42	-0.30	-0.98	-1.22	-0.89	-0.67	-0.87
		(0.51)	(0.23)	(0.68)	(-0.13)	(1.21)	(-0.55)	(-1.94)	(-1.65)	(-1.69)	(-0.94)	(-0.86)
	β_{IMC}	0.14	-0.01	0.10	0.06	0.07	0.15	-0.12	-0.11	-0.07	0.04	-0.10
		(1.41)	(-0.21)	(1.67)	(0.56)	(0.72)	(1.94)	(-1.01)	(-0.79)	(-0.59)	(0.26)	(-0.44)
IST+TFP:												
	β_{Ishock}	-1.78	-1.73	-1.61	-1.79	-1.22	-1.98	-2.49	-2.79	-2.47	-2.63	-0.85
		(-1.97)	(-2.26)	(-1.92)	(-1.77)	(-1.63)	(-2.12)	(-3.31)	(-2.80)	(-2.98)	(-2.39)	(-0.84)
	β_{IMC}	0.64	0.46	0.55	0.50	0.48	0.59	0.31	0.34	0.38	0.56	-0.08
		(3.13)	(2.56)	(3.47)	(2.82)	(2.48)	(3.69)	(1.45)	(1.51)	(1.89)	(2.24)	(-0.37)

Table 2: Parameter values

This table summarizes the two sets of alternative parameter values used in simulations. The first set, listed in column labeled "KP parameters", is mainly taken from Kogan and Papanikolaou (2014). The second set, listed in column labeled "Alternative parameters", reports only the parameter values that are different from the "KP parameters".

Parameter	Symbol	KP parameters	Alternative parameters
Technology, aggregate shocks			
Mean growth rate of the disembodied technology shock	μ_x	0.005	
Volatility of the disembodied technology shock	σ_x	0.135	
Mean growth rate of the IST shock	μ_z	0.002	
Volatility of the IST shock	σ_z	0.035	
Technology, idiosyncratic shocks			
Persistence of the firm-specific shock	θ_ε	0.350	
Volatility of the firm-specific shock	σ_ε	0.200	0.000
Persistence of the project-specific shock	θ_u	0.500	0.030
Volatility of the project-specific shock	σ_u	1.500	
Project arrival and depreciation			
Project depreciation rate	δ	0.100	
Arrival rate parameter 1	$\underline{\lambda}$	5.000	
Arrival rate parameter 2	$\overline{\lambda}$	25.000	
Transition probability into high-growth state	μ_H	0.075	
Transition probability into low-growth state	μ_L	0.160	
Ratio of arrival rates in high vs. low growth states	λ_H/λ_L	6.400	2.000
Stochastic discount factor			
Risk-free rate	r	0.030	
Price of risk of the disembodied shock	γ_x	0.690	
Price of risk of the IST shock	γ_z	-0.350	
Other			
Project-level return-to-scale parameter	α	0.850	
Profit margin of the investment sector	ϕ	0.070	

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