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Can Capital Adjustment Costs Explain the Decline in Investment–Cash Flow Sensitivity?

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Abstract

It is well documented that since at least the 1970s investment-cash flow (I-CF) sensitivity has been decreasing over time to disappear almost completely by the late 2000s. Based on a neoclassical investment model with costly external financing, we show that this pattern can be explained by the gradual increase of capital adjustment costs, attributable to the accumulation of knowledge capital. The result is robust to a variety of approaches, including Euler equation estimation and the simulated method of moments. More generally, our findings demonstrate that I-CF sensitivity should only be interpreted as a joint measure of financial and *real* frictions.

I. Introduction

One of the key research areas in corporate finance focuses on the effect of capital market imperfections on corporate investment. According to the standard q-investment model (Mussa (1977)), the optimality condition requires that the marginal value of capital (measured by the marginal q) be equal to the marginal cost of investment. In this framework, marginal q is the sole factor relevant to the investment level. Financial factors, such as cash flow, are expected (in the absence of capital market frictions) to play no role.

At the same time, a number of empirical studies that rely on a reduced-form regression model, in which investment is a dependent variable and q and cash flow

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are regressors, show that investment is sensitive to cash flow. Fazzari, Hubbard, and Petersen (1988) interpret this investment-cash flow (I-CF) sensitivity as the evidence of financial constraints as these are financially constrained firms that may link their investment to the availability of internal funds (see also, Hoshi, Kashyap, and Scharfstein (1991), Gilchrist and Himmelberg (1995), Lamont (1997), Rauh (2006), and Cao, Lorenzoni, and Walentin (2019)).

Fazzari et al.'s (1988) view of I-CF sensitivity as a measure of financial constraints has been challenged by, among others, Kaplan and Zingales (1997), Cleary (1999), Gomes (2001), Alti (2003), and Moyen (2004). Also, Erickson and Whited (2000) (2002) point out that the observed empirical I-CF sensitivity can be spurious as average Tobin's q is a not a valid proxy for investment opportunities, due to measurement error (see also, among many others, Bond and Cummins (2001), Cummins, Hassett, and Oliner (2006), and Ağca and Mozumdar (2017)). Inasmuch as empirical q fails to adequately capture investment opportunities, part of the information content about capital productivity is captured by cash flow (see, e.g., Gilchrist and Himmelberg (1995), Chen, Goldstein, and Jiang (2007)). Therefore, I-CF sensitivity can also be an outcome of the poor quality of an empirical proxy for marginal q.

Allayannis and Mozumdar (2004) are the first to exploit the time-series pattern and document declining I-CF sensitivity between periods 1977–1986 and 1987–1996. Their paper spurred a debate about the economic drivers behind the negative trend of I-CF sensitivity, which has since remained largely unresolved. Ağca and Mozumdar (2008) find that I-CF sensitivity decreases with factors that reduce capital market imperfections but do not directly link the decline of I-CF sensitivity over time to the evolution of those factors. Chen and Chen (2012) conclude that financial constraints cannot explain the declining pattern of I-CF sensitivity as there is no indication of financial constraints becoming more relaxed over time. They also document that the declining pattern of I-CF sensitivity still exists with measurement error-corrected estimates (Lewellen and Lewellen (2016) and Ağca and Mozumdar (2017) provide evidence consistent with that result). Although Brown and Petersen (2009), Moshirian, Nanda, Vadilyev, and Zhang (2017), and Wang and Zhang (2021) conjecture that the declining I-CF sensitivity is due to the shift of importance or productivity from physical capital to intangible assets, Chen and Chen (2012) show that it is also R&D-cash flow sensitivity that disappears by late 2000s.[1] Finally, although market power is another factor that can influence I-CF sensitivity (e.g., Cooper and Ejarque (2003)), the fact that many U.S. industries are becoming more concentrated over time (Grullon, Larkin, and Michaely (2019), De Loecker, Eeckhout, and Unger (2020)) should lead, if anything, to an upward (rather than the observed downward) trend.

In this article, we use a neoclassical investment model with costly external financing to demonstrate that the negative trend is due to the evolution of capital adjustment costs. To this end, we estimate the magnitude of the capital adjustment cost parameter(s) across different periods and show that there has been a gradual increase in the costs of capital adjustment, which is capable of explaining the decreasing I-CF

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[1] Brown and Petersen (2009) report that cash flow sensitivity of total investment (physical capital expenditure and R&D expense) still decreases across periods.

sensitivity pattern. Consistent with the prior literature, we find no evidence of financial frictions being able to significantly contribute to the observed trend.

We present our main argument in 4 steps. First, we empirically confirm the existence of the downward trend of both I-CF and I-*q* sensitivity by estimating corresponding regression coefficients over nonoverlapping 5-year periods using both OLS and generalized method of moments (GMM) approaches. The statistical significance of the negative trend of both coefficients is confirmed by estimating the model for the whole sample and including interaction terms between the regressors (cash flow and *q*) and time trend.

In the second step, we present an argument that the predicted magnitude of I-CF sensitivity is not only an increasing function of financing constraints but also a decreasing function of capital adjustment costs. The intuition behind the latter result is as follows: When a firm invests, it does not only increase its capital stock, which is recorded as capital expenditure, but also incurs capital adjustment costs.[2] Higher capital adjustment costs result therefore in a lower fraction of an incremental $1 of cash flow earmarked for investment being allocated to an increase of capital stock. Given that capital expenditure reacts less to the availability of internal funds when capital adjustment is more costly, a positive time trend of adjustment costs results in declining I-CF sensitivity.

The increasing capital adjustment costs argument is also consistent with the observed declining I-*q* sensitivity as the frictions in adjusting capital stock dampen the response of investment to the changes in growth opportunities captured by Tobin's *q*.[3] The presence of the negative trend of both I-CF and I-*q* sensitivity, documented in the previous step, supports the hypothesis that it is the gradual increase of capital adjustment costs over time that is the primary driver of the observed declining I-CF sensitivity pattern. Our results are therefore consistent with those in Chen and Chen (2012) in the sense of the declining I-CF sensitivity not being a symptom of decreasing financial constraints as well as with Pratap (2003), who demonstrates that capital adjustment costs can explain low I-CF sensitivity even for financially constrained firms. (The alternative hypothesis of decreasing financial constraints would imply an *increasing* trend of I-*q* sensitivity, which is contrary to the evidence presented in our paper.)

The third step of our analysis includes explicitly estimating the parameter(s) of the adjustment cost function together with a parameter that reflects the cost of accessing outside finance over each 5-year period. To achieve this objective and demonstrate the robustness of our results, we adopt a number of approaches here. We begin by directly estimating relevant parameters from the first-order condition of the intertemporal investment model using alternative measures of Tobin's *q*. As mismeasurement of *q* makes the task of identifying adjustment costs from an OLS regression of investment on *q* difficult, either due to spurious-significance or the nonlinearity problem (Whited (1998), Erickson and Whited (2000)), we estimate

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[2] Examples of capital adjustment costs include installation costs, costs of disrupting the production process and fees associated with training staff to adapt to the new equipment. More specific examples are provided in Section III.

[3] The intuition is similar to that behind the effect of adjustment costs on I-CF sensitivity, where adjustment costs act effectively as a tax on capital expenditure.

adjustment cost parameters based on the first-order condition which has Tobin's q as a left-hand-side variable to alleviate the measurement error problem (Erickson and Whited (2012)). We subsequently perform estimations on the basis of the Euler investment equation, which circumvents the use of a proxy for q. Finally, we also estimate the parameters of interest using the simulated method of moments (SMM) approach, where parameter values are selected to match the actual moments with simulated ones.[4] Taken together, our results provide robust evidence that capital adjustment costs have indeed increased over time.

In the fourth step, we investigate possible microfoundations of the positive trend of capital adjustment costs. Based on the extant literature and available data, we argue that the observed increase in capital adjustment costs is driven by investment in knowledge capital, which is associated with the adoption of new technologies (e.g., the widespread use of computers and software, network, and automated systems).[5] As the integration of the high-tech equipment and machinery entails complex implementation and relies on specialist skills for the subsequent operation, it typically results in costly installation, retrofitting, and retraining.[6] Overall, investment in knowledge capital, which results from technological progress as well as expanding new product markets, can translate into higher productivity but – on the downside – leads to increased adjustment costs.

Our analysis in this final step begins with demonstrating that knowledge capital increases over the sample period and that both I-CF and I-q sensitivities are negatively related to it. We subsequently parameterize the scaling parameter of the adjustment cost function in the Euler equation and demonstrate a positive relationship of this parameter with the knowledge capital. Subsequently, we extend the intertemporal investment model of Section IV to also include (optimal) investment in knowledge capital and use SMM to show that capital adjustment costs as a function of knowledge capital do increase over time.

The article contributes to the literature on corporate investment and financing decisions in several ways. First, we provide systematic evidence that, since 1970s, there has been an increasing trend of capital adjustment costs. The relevance of capital adjustment costs for investment is discussed, among others, in Barnett and Sakellaris (1998), (1999), Whited (1998), Abel and Eberly (2002), Basu, Fernald, Oulton, and Srinivasan (2003), Pratap (2003), Cooper and Haltiwanger (2006), Caggese (2007), and Groth and Khan (2010).[7] Also, while investment is reliant on

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[4] The linkage of model parameters with I-CF sensitivity is related to several other studies that use the structural modeling approach, such as Gamba and Triantis (2008) and Riddick and Whited (2009).

[5] According to PwC (2016), "the use of 3D printing is disrupting U.S. manufacturing" and "the most commonly cited barriers to the adoption is the cost and lack of talent and current expertise." Factories are switching to electric vehicles, which bring "new ways of structuring transportation, land use and domestic energy use" but, at the same time, require costly investment in the associated infrastructure (Barkenbus (2009)).

[6] Clegg (2018) reports that the online education program funded by AT&T to retrain the workforce "requires at least 10 hours' homework a week and takes 6–12 months to complete" and SEAT's (the Spanish subsidiary of the Volkswagen Group) reskilling program opens the possibility for employees to retrain during working hours.

[7] Capital adjustment costs can also be an important source of business cycle fluctuations. For instance, Basu et al. (2003) argue that capital adjustment costs account for the underlying deceleration of productivity growth in the United Kingdom.

cash flow when it is costly to access the external financing market, it is *less sensitive* to cash flow in the presence of higher capital adjustment costs. Second, using a number of empirical approaches, we demonstrate that it is the increasing magnitude of frictions generated by capital adjustment that contribute to the declining I-CF sensitivity over time. We, therefore, highlight the role of frictions generated by the *real* side of firms' activities in explaining the evolution of the responsiveness of investment to internal funds as opposed to frictions generated by financial markets. Finally, we provide evidence that the documented increase of adjustment costs is one of the consequences of an increase in the stock of knowledge capital, which firms optimally accumulate to increase their productivity.

II. Dataset and Baseline Results

The sample contains all U.S. manufacturing firms (SIC between 2000 and 3999) in the Compustat industry annual file, covering the period between 1977 and 2019. Investment (I) is measured as capital expenditure in a year (CAPX). Capital (K) is defined as beginning-of-year net property, plant, and equipment (PPENT). Tobin's average $q(Q)$ is the beginning-of-the-year market value of capital over net property, plant, and equipment. The market value of capital is defined as the market value of assets minus the difference between the book value of assets (AT) and the book value of capital (PPENT).[8] The market value of assets is the sum of market value of common stock (CSHO × PRCC), total liabilities (LT), and preferred stock (PSTK) minus deferred taxes (TXDITC). Cash flow (CF) is income before extraordinary items (IB) plus depreciation and amortization (DP).

Regression variables (i.e., I/K, Q, and CF/K) are required to have nonmissing values for each observation. Following Almeida, Campello, and Weisbach (2004), we remove firms that have sales or asset growth exceeding 100% to eliminate the effect of business discontinuities. We also drop firms that have assets, sales, or capital lower than USD 1 million (see Chen and Chen (2012), Moshirian et al. (2017)). Finally, following Hennessy and Whited (2007), we winsorize all regression variables at the 1% and 99% levels by year to mitigate the effect of outliers.[9]

Table 1 provides summary statistics for the regression variables. We divide the sample into 5-year subsample periods, except for the latest period for which only 3 years of data are available, and provide descriptive statistics for each period. The mean and median levels of I/K are relatively stable over time and broadly fluctuate around 0.2 across the sample period. The mean level of Q increases from 1.335 to 15.105 between 1977–1981 and 2017–2019, with its median level increasing from 0.815 to 5.596 over the same period. Both the 25th and 75th percentiles of Q increase over time too, which suggests that the positive trend of Q is not limited to the subsample of value firms or growth firms. The mean level of CF/K drops

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[8] Note that by subtracting the difference between the values of total assets and physical capital, we remove the value of intangible assets when calculating the market value of physical capital. This allows us to measure investment opportunities for the physical capital.

[9] The resulting dataset is an unbalanced panel, with a noticeable turnover of firms, in particular around the 2007–2009 Great Recession (the number of firms in period 1977–1981 (2007–2011) is 2045 (1786) and out of the 2045 firms present in years 1977–1981, 389 firms remain in the sample until period 2007–2011).

TABLE 1

Summary Statistics for Regression Variables

Table 1 reports the mean, standard deviation, percentiles, and first-order serial correlation ρ_k for variable $k \in \{I/K, Q, \text{CF}/K\}$ for each subsample period (1977–1981 to 2017–2019). I/K is the firm's capital expenditure, scaled by beginning-of-year net property, plant, and equipment. Q is the beginning-of-year average Tobin's q, calculated as the market value of capital divided by the book value of capital (measured by net property, plant, and equipment). CF$/K$ is firm's internal cash flow (income before extraordinary items plus depreciation), deflated by beginning-of-year net property, plant, and equipment. The sample contains all manufacturing firms (SIC code between 2000 and 3999) in the United States for which relevant data is available in Compustat over 1977–2019 period.

Period	1977–1981	1982–1986	1987–1991	1992–1996	1997–2001	2002–2006	2007–2011	2012–2016	2017–2019
I/K									
Mean	0.287	0.260	0.239	0.270	0.262	0.225	0.235	0.240	0.230
Std. Dev.	0.215	0.228	0.197	0.243	0.240	0.225	0.227	0.213	0.198
p(25)	0.150	0.120	0.114	0.119	0.110	0.090	0.097	0.112	0.109
p(50)	0.233	0.198	0.190	0.199	0.191	0.156	0.170	0.183	0.178
p(75)	0.351	0.320	0.297	0.333	0.327	0.276	0.289	0.288	0.281
$\rho_{I/K}$	0.458	0.390	0.430	0.513	0.452	0.494	0.471	0.530	0.573
Q									
Mean	1.335	2.501	3.088	5.116	6.547	9.267	9.448	11.930	15.105
Std. Dev.	1.992	3.529	4.628	8.288	12.250	17.886	18.283	25.867	30.026
p(25)	0.322	0.704	0.891	1.145	1.135	1.325	1.323	1.545	1.930
p(50)	0.815	1.373	1.680	2.333	2.575	3.362	3.529	4.005	5.596
p(75)	1.693	2.898	3.358	5.291	6.437	8.873	9.278	10.584	14.590
ρ_Q	0.819	0.766	0.798	0.771	0.682	0.723	0.752	0.811	0.845
CF$/K$									
Mean	0.415	0.307	0.267	0.327	0.067	0.035	−0.009	−0.143	−0.506
Std. Dev.	0.350	0.490	0.681	0.982	1.512	2.091	2.525	3.289	4.608
p(25)	0.235	0.135	0.108	0.136	0.010	−0.011	−0.057	0.069	0.014
p(50)	0.377	0.295	0.280	0.328	0.286	0.309	0.343	0.372	0.353
p(75)	0.559	0.495	0.490	0.603	0.588	0.692	0.802	0.806	0.829
$\rho_{\text{CF}/K}$	0.754	0.687	0.627	0.627	0.627	0.692	0.651	0.729	0.795

substantially, from 0.415 in 1977–1981 to −0.506 in 2017–2019, with its median level remaining relatively stable. There is also an increasing cross-sectional variation in Q and CF$/K$ as indicated by greater dispersion between the 25th and 75th percentiles and larger standard deviations.

Serial correlation of the investment-to-capital ratio indicates the smoothness of investment behavior, which is symptomatic of convex adjustment costs, and rises from 0.458 in years 1977–1981 to 0.573 in the most recent period. The proxy for Tobin's q is also highly autocorrelated, which has implications for the use of lagged instrumental variables to correct for the measurement error in q (Almeida, Campello, and Galvao (2010), Erickson and Whited (2012)).

The baseline OLS regression equation for investment is

$$\frac{I_{it}}{K_{it}} = \beta_0 + \beta_1 Q_{it} + \beta_2 \frac{\text{CF}_{it}}{K_{it}} + \eta_i + \xi_t + \varepsilon_{it}, \tag{1}$$

where $\beta_i, i \in \{0,1,2\}$ denotes the relevant regression coefficient, η_i is the firm fixed effect, ξ_t is the year-fixed effect, and ε_{it} is an error term. Next to the OLS estimator, we also use the Erickson and Whited ((2000), (2002)) higher-order moment-based GMM estimator (EW estimator), which is designed to mitigate the consequences of measurement error in Q_{it}. We employ the fifth-order moment-based GMM estimator (GMM5) and a within-transformation is applied to all independent variables to remove the individual fixed effect.

Panel A of Table 2 presents baseline regression results for each subsample period from 1977–1981 to 2017–2019. For 1977–1981, I-CF sensitivity (β_2) equals 0.271 and is statistically significant. I-CF sensitivity decreases in subsequent

TABLE 2

Baseline Linear Regression Results

Table 2 reports the estimation results of regression models for both OLS and GMM5 estimators for each subsample period (Panel A) and the whole sample with an interaction with TREND (Panel B). The dependent variable (I/K) is investment measured as the firm's capital expenditure, scaled by beginning-of-year net property, plant and equipment. The independent variables are the beginning-of-year Tobin'q (Q), defined as the market value of capital over book value of capital (measured by net property, plant, and equipment), and cash flow (CF/K), defined as income before extraordinary items plus depreciation, deflated by beginning-of-year net property, plant and equipment. TREND is defined as 1 in 1977–1981, 2 in 1982–1986 and so on. β_1 (β_2) denotes the coefficient of Q (CF/K). Robust standard errors (in parentheses) are clustered at the firm level. TREND is absorbed by year-fixed effects in the OLS estimation. The sample contains all U.S. manufacturing firms in Compustat over 1977–2019 period. ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

Panel A. Estimation Results per Subsample Period

	OLS		GMM5		
Period	β_1	β_2	β_1	β_2	No. of Obs.
1977–1981	0.021***	0.271***	0.101***	0.207***	7,994
	(0.004)	(0.021)	(0.009)	(0.020)	
1982–1986	0.022***	0.131***	0.060***	0.069***	8,033
	(0.003)	(0.015)	(0.006)	(0.016)	
1987–1991	0.016***	0.058***	0.037***	0.046***	7,714
	(0.002)	(0.009)	(0.003)	(0.009)	
1992–1996	0.010***	0.046***	0.026***	0.022***	8,357
	(0.001)	(0.008)	(0.002)	(0.008)	
1997–2001	0.007***	0.022***	0.016***	0.022***	8,680
	(0.001)	(0.006)	(0.002)	(0.006)	
2002–2006	0.006***	0.005	0.012***	0.002	7,497
	(0.001)	(0.005)	(0.001)	(0.005)	
2007–2011	0.007***	0.000	0.010***	−0.002	6,436
	(0.001)	(0.004)	(0.000)	(0.003)	
2012–2016	0.004***	−0.002	0.008***	−0.001	5,451
	(0.001)	(0.004)	(0.001)	(0.004)	
2017–2019	0.003***	−0.004	−0.001	−0.009	2,917
	(0.001)	(0.004)	(0.001)	(0.005)	

Panel B. Estimation Results for the Whole Sample with TREND

	Q_{it}	$\frac{CF_{it}}{K_{it}}$	Q_{it} × TREND	$\frac{CF_{it}}{K_{it}}$ × TREND	TREND
OLS	0.016***	0.089***	−0.002***	−0.011***	
	(0.001)	(0.005)	(0.000)	(0.001)	
GMM5	0.008***	0.025***	−0.0002***	−0.001***	−0.021***
	(0.000)	(0.002)	(0.000)	(0.000)	(0.001)

periods and from 2002 to 2006 onward becomes nonsignificant, consistent with Chen and Chen (2012). A similar decreasing pattern is observed when the EW estimator is applied, which indicates that the decreasing trend of I-CF sensitivity is unlikely to be driven by a potential measurement error. Moreover, a declining trend is also observed for I-q sensitivity, as evidenced by decreasing coefficient β_1 between 1977–1981 and 2017–2019. In Panel B of Table 2, we provide statistical evidence that I-CF and I-q sensitivity are decreasing over time by interacting cash flow and q with the trend variable (denoted as TREND) which is equal to 1 in 1977–1981, 2 in 1982–1986 and so on. The coefficients of Q_{it} × TREND and $\frac{CF_{it}}{K_{it}}$ × TREND are negative and, therefore, confirm the results of the subsample analysis.

In Section III, we reconcile the above results with the predictions of investment theory and argue that it is the evolution of capital adjustment costs that is consistent with the observed trends of I-CF and I-q sensitivities.

III. Capital Adjustment Costs and I-CF Sensitivity

The extant literature on I-CF sensitivity has largely focused on the effects of financial constraints (e.g., Ağca and Mozumdar (2008), Chen and Chen (2012)). Yet, relatively little attention has been devoted to investigating the impact of capital adjustment costs on the responsiveness of investment to extra cash flow.

Capital adjustment costs are the expenditure incurred before the equipment or plant can be put to full use and comprise installing costs (e.g., breaks in production during installation and sunk costs), learning, expenses associated with the training of labor to accommodate new physical capital, lost expertise due to the adoption of new technologies, overtime costs, costs of disrupting the old system and reorganizing the production process. Cooper and Haltiwanger (2006) state that "changing the level of capital services at a business generates disruption costs" and that "installing new equipment or structures often involves delivery lags and time to build." Kiley (2001) concludes that adjustment costs related to the installation of high-tech equipment, such as the cost of training workers to use a new technology and reorganizing activities associated with the installation of new capital, are of first-order importance. Brown, Fazzari, and Petersen (2009) argue that R&D involves spending on highly skilled technology workers who are costly to hire, train and replace, and thus exhibits high capital adjustment costs (see also Peters and Taylor (2017)).[10] From the perspective of sustainability, costs may occur to meet the high environmental standards when repurposing existing plants or constructing new sites.

If firms had an unrestricted access to external finance, they would be able to invest whenever valuable projects arise and the availability of internal funds would be irrelevant. With a costly access to external capital markets, the sensitivity of investment to cash flow – irrespective of the level of adjustment costs – is expected to be positive. As it is therefore possible that the decreasing I-CF sensitivity is the result of a better access to external financing (cf. Ağca and Mozumdar (2017)), we formulate the following empirical prediction:

Hypothesis 1. Cash flow sensitivity of investment decreases as a result of lower costs of external financing.

I-CF sensitivity does not only depend on the costs of obtaining outside financing but also on the costs of adjusting the level of capital stock (e.g., Lewellen and Lewellen (2016)). Higher adjustment costs result in a lower fraction of an extra dollar of cash flow earmarked for investment being actually spent on new capital stock as its increased fraction is used to cover the associated costs of capital

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[10] Capital adjustment costs tend to be explicitly mentioned in company reports. Nestlé Group ((2016), p. 16) has expensed the costs of disruption as "impairment of property, plant or equipment," which are mainly related to about "the plans to optimize industrial manufacturing capacities by closing or selling inefficient production facilities," with the expenses amounting to more than CHF 200 million. Equipment and facilities used for manufacturing can also be subject to a costly technological change. According to Intel Corporation ((2016), p. 36), the increase of the company's R&D spending comes in a significant part from high development costs of a new processor technology. Manufacturers of semiconductors now face "increased costs of constructing new fabrication facilities to support smaller transistor geometries."

adjustment. Consequently, financially constrained firms increase their investment to a smaller extent upon receiving cash windfall when capital adjustment is costly. Therefore, an alternative explanation for the decreasing I-CF sensitivity over time is the gradually increasing adjustment costs. Hence, we formulate the second empirical prediction:

Hypothesis 2. Cash flow sensitivity of investment decreases due to higher capital adjustment costs.

The above discussion implies that the changes in I-CF sensitivity may be a joint result of the evolution of both financing constraints as well as capital adjustment costs. What is worth pointing out is that the imperfections on the real side of firm's activities (adjustment costs) have an opposite effect on this sensitivity compared to imperfections in financial markets (financing constraints).

Regarding the effect of growth opportunities (Tobin's q) on investment, capital expenditure will be less sensitive to changes in q if the firm is constrained by frictions in either financial markets or real economic activities. This is due to the fact that both types of frictions effectively increase the marginal cost of investment. With that observation in mind, we offer a preliminary test of our predictions by looking back at the time trend of I-q sensitivity. If I-CF sensitivity declines alongside with the decrease of financial constraints, we should observe an increasing trend of I-q sensitivity. In the alternative case, if I-CF sensitivity declines as a result of higher capital adjustment costs in late years, we should observe a decreasing trend of I-q sensitivity as well.

The baseline OLS regression results in Table 2 indicate both a declining q sensitivity of investment as well as a downward-sloping I-CF sensitivity. This combination of results supports the second prediction (i.e., Hypothesis 2) that decreasing I-CF sensitivity is driven by rising capital adjustment costs.

IV. Evidence on Increasing Capital Adjustment Costs

Given the documented shortcomings of the OLS (and to a certain extent GMM) estimators when the regressors, such as q, are measured with an error (cf. Erickson and Whited (2000), (2002), (2012), Almeida et al. (2010)), in Sections IV and V we provide a broader empirical assessment of the evolution of capital adjustment costs and financial frictions.

We first introduce a simple intertemporal model of investment with financial constraints and adjustment costs. We then derive the first-order condition of the investment problem and estimate its parameters of interest using regression analysis. We then proceed to estimating relevant model parameters using the Euler equation framework as well as SMM.[11]

In the adopted setup, time is discrete, I is current investment, and K is capital stock. K satisfies the standard intertemporal condition $K' = I + (1-\delta)K$, where prime ($'$) denotes the next period's value and $\delta \geq 0$ is the depreciation rate.

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[11] In Appendix OA1 of the Supplementary Material, we report the results of an analysis based on industry-level data and present evidence consistent with a positive trend of capital adjustment costs.

Adjusting capital stock is costly and the adjustment cost function is given by $G(I,K)=\psi^{-1}\gamma(I/K)^{\psi}K$, where $\gamma>0$ is a scaling parameter and $\psi>1$ reflects the elasticity of adjustment cost with respect to investment rate. The assumed convex adjustment costs incentivize firms to smooth investment, which results in only a partial adjustment of capital toward its desired level, and leads to positive serial correlation of investment (see, e.g., Cooper, Haltiwanger, and Power (1999), Caballero and Engel (2003), Fiori (2012), and Chen, Jiang, Liu, Serrato, and Xu (2023)). The demonstrated evidence of the presence of convex adjustment costs (e.g., Hayashi (1982), Kogan (2004), and Cao et al. (2019)) is also consistent with Wang and Wen (2012), where borrowing constraints may result in the convexity of the adjustment cost function (see also Carlstrom and Fuerst (1997)).

Although Cooper and Haltiwanger (2006) report that serial correlation of investment is low at the plant level (estimated at 0.058), we show that serial correlation is economically significant at the firm level (see Table 1). To further support the choice of the convex adjustment cost formulation, we test for convexity of function $G(I,K)$ later in this section.

The profit function, which also constitutes a measure of internal funds available for investment, is denoted by $\Pi(A,K)$, where A is a Markovian state variable. The cost of external financing, $H(X,K)$, is a function of amount $X\equiv I-\Pi$ that a firm needs to raise externally to meet its investment needs.[12] We follow Lewellen and Lewellen (2016) and define $H(X,K)\equiv 0.5b\Phi(X/K)^2K$, where Φ is an indicator equal to 1 if $I\geq\Pi$, and 0 otherwise. Parameter b is a scaling factor reflecting the cost of external financing. A ceteris paribus higher (unit) cost of raising funds from the outside capital market is equivalent to a higher magnitude of financing constraints.

Equityholders choose an investment policy to maximize the firm value:

$$V(A,K)=\max_{I}\left[(\Pi(A,K)-I-G(I,K)-H(X,K))+\vartheta E_{A'|A}V(A',K')\right], \tag{2}$$

where ϑ is a discount factor. The marginal Tobin's q (denoted by q) is defined as $\vartheta E_{A'|A}V_K(A',K')$, where $V_K\equiv\partial V/\partial K$. The first-order condition with respect to I yields the following equation for q:

$$1+\gamma\left(\frac{I}{K}\right)^{\psi-1}+b\Phi\left(\frac{I}{K}-\frac{\Pi}{K}\right)=q. \tag{3}$$

Equation (3) states that at the optimal investment level, the marginal cost of investment equals its marginal benefit. The marginal cost consists of a unit price of capital (normalized to 1), the marginal cost of capital adjustment and, for insufficient internal funds, the marginal cost of external financing. The condition thus implies that higher capital adjustment costs raise the marginal cost of investment, which makes changes in capital stock less responsive to both q and cash flow.

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[12] As in Cooper and Ejarque (2003) and Lewellen and Lewellen (2016), X equals the gap between investment and cash flow and ignores the capital adjustment cost. Including the latter in X results in more complex calculations but does not substantially affect the main results.

A. Direct Estimation of b and γ Based on the q Equation

To alleviate any consequences of the potential measurement problem in q, instead of relying on the baseline linear regression (1), in which q and cash flow are regressors, we directly provide estimates of model parameters b, γ, as well as ψ, based on the first-order condition (3). We let q become the dependent variable so we can still obtain consistent estimates of parameters as long as the measurement error is independent of the explanatory variables.

The empirical equivalent of (3) is

$$Q_{it} = 1 + \gamma \left(\frac{I_{it}}{K_{it}} \right)^{\psi - 1} + b\Phi \left(\frac{I_{it}}{K_{it}} - \frac{\text{CF}_{it}}{K_{it}} \right) + \eta_j + \xi_t + \varepsilon_{it}, \tag{4}$$

where η_j is dummy variable for each 2-digit SIC industry code and ξ_t represents the year-fixed effect.[13] Other variables are as those described in Section II. Estimated parameters are all expected to be positive (and are, therefore, restricted to nonnegative values). The estimation procedure yields the set of parameters that minimizes the sum of squared errors $\sum \varepsilon_{it}^2$. The estimation results are presented in Panel A of Table 3.

Given that the likely mismeasured Q is the dependent variable, the estimates of the parameters based on equation (4) are more reliable than the ones implied from the reciprocal of β_1 and the ratio of β_2 and β_1 from regression (1). The R^2 shown in column 5 indicates that the model's goodness-of-fit improves over time, which is consistent with the finding in Chen and Chen (2012) that the measurement quality of Tobin's q is improving.

The estimates of parameter b, which measures the cost of external financing, are reported in column 4. The estimated b is in most periods positive and significant (apart from 1977 to 1981, when it is not significantly positive) and generally higher in 2000s than in earlier periods. If one interprets I-CF sensitivity as a measure of financial constraints, one would expect to see a declining b over time, which would correspond to a negative trend of coefficient β_2 in equation (1). The degree of financial constraints, as captured by b, is, however, increasing. This result is consistent with Chen and Chen's (2012) evidence that financial constraints have *not* become more relaxed in recent years. Also, constrained firms are more inclined to hold cash (Almeida et al. (2004), Faulkender and Wang (2006)), with Bates, Kahle, and Stulz (2009) showing that there is an increase in cash holdings of U.S. firms. Therefore, we again do not find support for Hypothesis 1 that decreasing financial constraints explain the negative trend of I-CF sensitivity.

The estimate of scaling parameter γ of the adjustment cost function, reported in column 2, increases systematically throughout the sample period. This positive trend is consistent with I-CF sensitivity declining over time. Investment responds less strongly to cash flow in late periods because capital adjustment is more costly.

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[13] We use industry fixed effects instead of firm fixed effects, as, otherwise, regressions may fail to capture the characteristics of firms that have single observations during the 5-year subsample period. In our sample, between 10%–17% of firms (depending on the model specification) have only a single observation, and around 30% of firms (with the exact number depending again on the specification) have two observations in the subsample period.

TABLE 3
Estimation Results Based on the q Equation

Estimation results in Panel A of Table 3 are based on equation (4) in each 5-year subsample period where Q_{it} is defined as the beginning-of-year Tobin's average q, b is external financing cost parameter, γ is a scaling parameter of the adjustment cost function, ψ measures its elasticity ($\psi = 2$ if the adjustment cost function is quadratic). Column 6 in Panel A reports t-statistics under the null hypothesis that $\psi = 2$. The estimation in Panel B assumes a quadratic adjustment cost function and is based on the alternative measures of q. R^2 in both Panels A and B is 1 minus mean squared error divided by the variance of Q_{it}, defined as Gala et al.'s marginal q and fundamental q, respectively. Robust standard errors for each parameter are reported in the parentheses.***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

Panel A. Estimation of q Equation with Tobin's q

Period	γ	ψ	b	R^2	$t(\psi = 2)$
1977–1981	2.701***	2.150***	0.000	0.214	1.620
	(0.353)	(0.093)	(0.250)		
1982–1986	5.570***	1.970***	0.250	0.224	−0.549
	(0.159)	(0.054)	(0.191)		
1987–1991	6.726***	2.165***	1.141***	0.168	1.381
	(0.670)	(0.119)	(0.378)		
1992–1996	13.119***	2.004***	2.502***	0.261	0.035
	(1.279)	(0.121)	(0.685)		
1997–2001	17.958***	1.853***	2.149***	0.246	−3.181***
	(0.659)	(0.046)	(0.515)		
2002–2006	30.513***	2.117***	2.700***	0.333	5.118***
	(1.592)	(0.023)	(0.168)		
2007–2011	27.520	2.179***	2.520***	0.313	1.973**
	(1.503)	(0.091)	(0.997)		
2012–2016	33.959***	2.116***	3.400***	0.367	1.218
	(1.351)	(0.095)	(0.478)		
2017–2019	43.026***	1.719***	2.709***	0.315	2.026**
	(3.740)	(0.139)	(0.344)		

Panel B. Estimation of q Equation with Alternative Measures of q

Gala et al.'s Marginal q				Fundamental q			
Period	γ	b	R^2	Period	γ	b	R^2
1977–1981	0.029	0.000	0.038	1977–1981	1.072***	0.000	0.123
	(0.231)	(0.152)			(0.370)	(0.155)	
1982–1986	0.200	0.133	0.032	1982–1986	1.468**	0.000	0.126
	(0.392)	(0.486)			(0.783)	(0.880)	
1987–1991	0.348	0.179	0.002	1987–1991	2.374**	0.000	0.121
	(0.397)	(0.439)			(0.943)	(1.401)	
1992–1996	0.823	0.486	0.005	1992–1996	4.005**	0.000	0.164
	(1.126)	(0.714)			(2.307)	(1.189)	
1997–2001	1.451	0.073	0.117	1997–2001	3.599	0.220	0.110
	(1.388)	(0.113)			(3.583)	(0.406)	
2002–2006	2.493*	0.217	0.006	2002–2006	9.014**	0.031	0.125
	(1.736)	(0.294)			(4.408)	(0.400)	
2007–2011	3.813*	0.209	0.079	2007–2011	10.037**	0.966	0.208
	(2.188)	(0.196)			(4.552)	(1.048)	
2012–2016	4.213*	0.148	0.163	2012–2016	10.646**	1.015	0.178
	(2.338)	(0.177)			(5.533)	(1.170)	
2017–2019	6.291***	0.195	0.079	2017–2019	8.572***	0.709	0.174
	(2.160)	(0.105)			(4.984)	(0.950)	

Our result therefore echoes the conclusion of Pratap (2003) that in the presence of adjustment costs "investment cannot increase with marginal increases in cash flow [for some firms], leading to insensitivity of investment to cash flow." We obtain that sufficiently high adjustment costs imply low (and, empirically, statistically not significant) I-CF sensitivity even when financing constraints are present.[14] With respect to the magnitude of γ, earlier studies, which typically assume quadratic costs and infer the adjustment cost parameter from the reciprocal of the coefficient of q, obtain generally too high estimates for γ for them to be plausible (Gilchrist and Himmelberg (1995) obtain an estimate of γ as high as 20 during 1985–1989, which is similar to Hayashi (1982), who uses data from 1952 to 1978).[15]

Lower and thus more realistic estimates of γ are obtained in more recent studies that rely on dynamic models of a firm (e.g., Barnett and Sakellaris (1999), DeAngelo, DeAngelo, and Whited (2011), Nikolov and Whited (2014), and Gao, Whited, and Zhang (2021)). Adjustment cost parameter γ estimated in our setting falls into that more plausible range (and varies between 2.701 and 6.726 for the comparable period 1977–1991).

The estimates of the elasticity parameter ψ are reported in column 3. For most periods, they are not different from 2 at the 1% significance level (column 6 presents the t-statistics under the null hypothesis that $\psi = 2$), which supports the commonly used quadratic cost assumption (e.g., Gilchrist and Himmelberg (1995), Barnett and Sakellaris (1999), Nikolov and Whited (2014), and Lewellen and Lewellen (2016)) and, more generally, confirms the convexity of the adjustment cost function. Hence, from now on, we adopt a quadratic function for capital adjustment costs. One advantage of such a functional form is that it allows for interpreting an increase in the level of adjustment costs as an increase in γ, as the scaling parameter is the only one in the quadratic adjustment cost function.[16]

As average q (market-to-book capital ratio) may not be a reliable proxy for marginal q, if any of the linear homogeneity assumptions in Hayashi (1982) do not hold, we rerun the estimation with alternative measures of q: a state-space measure of marginal q (Gala, Gomes, and Liu (2020)) and the fundamental q (Goyal and Yamada (2001), Campello and Graham (2013)).[17]

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[14] Our result is based on a slightly different mechanism than in Pratap (2003) though. While her conclusion follows from the lack of investment in the "inaction region" characteristic for nonconvex adjustment costs, ours reflects negligible sensitivity of investment to cash flow for sufficiently high *convex* costs.

[15] Quadratic adjustment costs are assumed in the derivation of the baseline investment regression. Under such an assumption, an additional \$1 of investment leads to an incremental capital adjustment cost of $\$\gamma I/K$.

[16] In the same way, parameter b is synonymous with the magnitude of financing constraints.

[17] To calculate Gala et al.'s q, we infer the magnitude of profitability shock from net profit (as $A = \Pi/K^{\alpha}$), given the provided estimate of the curvature of the profit function ($\alpha = 0.51$). We denote the average q (market-to-book capital ratio) by Q and estimate $\log(Q) = a_0 + a_1 \log(A) + a_2 \log(K) + a_3 \log(A)^2 + a_4 \log(K)^2 + a_5 \log(A)\log(K) + \varepsilon$ in each subsample period. By doing so, we obtain the fitted value of Q ($\widehat{Q}$) as well as coefficient sets for capital stock and the profitability shock. Since the marginal q can be written as $q = \partial V/\partial K = V/K(1 + \partial\log(Q)/\partial\log(K))$, one can compute marginal q by differentiating the expression for $\log(Q)$ to obtain $q = \widehat{Q}(1 + \widehat{a}_2 + 2\widehat{a}_4 \log(K) + \widehat{a}_5 \log(A))$. The fundamental q is the portion of the market-to-book ratio that can be explained by observable fundamental variables, which are the lagged value of cash flow-to-capital ratio, sales growth, current asset-to-capital ratio, debt-to-capital ratio, capital spending, capital expenditure, size (market capitalization), industry sales growth, industry capital investment growth, and industry R&D growth.

The results with Gala et al.'s q (reported on the left-hand side of Panel B of Table 3) show that the estimate of the adjustment cost parameter γ rises across periods from 0.029 in 1977–1981 to 6.291 in 2017–2019. The estimation results based on the fundamental q (reported on the right-hand side of Panel B) yield a similar picture – the adjustment cost parameter γ increases steadily over time from 1.072 in 1977–1981 to 8.572 in 2017–2019. The results based on the alternative measures of q support the earlier conclusion that the financing cost parameter does not decrease over time and that the upward trend of the adjustment cost parameter is clearly present.

B. Empirical Implementation of the Euler Equation

As a complementary way of estimating capital adjustment costs, we use the investment Euler equation framework. The approach, which is based on equating the marginal cost of investment today with the expected discounted cost of waiting to invest tomorrow, does not require a proxy for q and mitigates endogeneity concerns present in the reduced-form regression framework (Kang, Liu, and Qi (2010)). To perform the estimation, we first express the maximization problem (2) as

$$(5)\quad V(A_t,K_t)=\max_{\{K_{\tau+1},I_\tau\}_{\tau=t}^{\infty}} E_t\sum_{\tau=t}\vartheta^{\tau-t}[\Pi(A_\tau,K_\tau)-I_\tau-G(I_\tau,K_\tau)-H(X_\tau,K_\tau)],$$

subject to $K_{\tau+1}=I_\tau+(1-\delta)K_\tau$. The right-hand side of equation (5) is the expected net present value of cash flows, which takes into account the expected quadratic adjustment cost as well as the cost of financing constraints. Following Gomes, Yaron, and Zhang (2006), we assume linear homogeneity of the profit function $\Pi(\cdot)$.[18] By differentiating (5) with respect to K_{t+1} and adding an error term ε_{t+1}, where $E_t(\varepsilon_{t+1})=0$, to remove the expectation operator (details are presented in Appendix OA2 of the Supplementary Material), we arrive at the estimation equation for the Euler equation:

$$(6)\quad \begin{aligned}&\vartheta\Bigg[(1-\delta)\left(1+\gamma\left(\frac{I_{t+1}}{K_{t+1}}\right)+b\Phi\left(\frac{I_{t+1}}{K_{t+1}}-\frac{\Pi_{t+1}}{K_{t+1}}\right)\right)\\&\quad+\frac{\Pi_{t+1}}{K_{t+1}}+\frac{1}{2}\gamma\left(\frac{I_{t+1}}{K_{t+1}}\right)^2+\frac{b}{2}\Phi\left(\frac{I_{t+1}}{K_{t+1}}-\frac{\Pi_{t+1}}{K_{t+1}}\right)\left(\frac{I_{t+1}}{K_{t+1}}+\frac{\Pi_{t+1}}{K_{t+1}}\right)\Bigg]+\varepsilon_{t+1}\\&\quad=1+\gamma\left(\frac{I_t}{K_t}\right)+b\Phi\left(\frac{I_t}{K_t}-\frac{\Pi_t}{K_t}\right).\end{aligned}$$

We follow Whited (1998) and employ the 2-step GMM to estimate the parameters in equation (6). As information set at time t is orthogonal to the error at time $t+1$, we use moment condition $E(Z_t\varepsilon_{t+1})=0$, where Z_t denotes the set of instruments: time fixed effects, the lagged value of investment-to-capital ratio, cash flow-to-capital ratio, debt-to-capital ratio, current assets-to-capital ratio, capital spending, sales growth, and cash reserves. We also set $\vartheta=(1+0.05)^{-1}$ (as in Gamba and Triantis (2008)). The estimation output is presented in Table 4. The

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[18] The linear homogeneity assumption implies that $\partial\Pi/\partial K=\Pi/K$.

TABLE 4

Estimation Results Based on the Investment Euler Equation

Table 4 reports the 2-step GMM estimation results of equation (6). The instrument set consists of time-fixed effects, lagged value of investment-capital ratio, cash flow-capital ratio, debt-capital ratio, current asset-capital ratio, capital spending, sales growth, and cash reserves. The weighting matrix in the first step is identity matrix and the weighting matrix for the second step is the inverse of robust standard errors clustered at firm level. Standard errors clustered at firm level for the estimated coefficients are reported in the parentheses. The *J*-statistics and the corresponding *p*-values (reported in parentheses) are presented in column 4. ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

Period	γ	b	J-Stat.
1977–1981	0.428***	0.000	390.615
	(0.075)	(0.179)	(0.000)
1982–1986	−0.159**	0.000	324.293
	(0.058)	(0.102)	(0.000)
1987–1991	0.908***	0.000	23.705
	(0.119)	(0.084)	(0.022)
1992–1996	0.247	1.762***	58.320
	(0.265)	(0.234)	(0.000)
1997–2001	1.300***	0.151***	30.046
	(0.183)	(0.058)	(0.003)
2002–2006	1.654***	0.395***	46.388
	(0.505)	(0.077)	(0.000)
2007–2011	6.192***	0.198***	19.960
	(0.633)	(0.046)	(0.068)
2012–2016	8.141***	0.222***	12.388
	(1.285)	(0.060)	(0.415)
2017–2019	24.276***	0.314	13.649
	(3.908)	(0.094)	(0.560)

results of the J test indicate that the overidentifying restrictions are rejected in most of the early periods (column 4). This can be largely expected due to the large cross-sectional variations in the data (Gomes et al. (2006)). The J-statistic decreases over time, which demonstrates that the model's goodness-of-fit improves in the later periods. The estimate of adjustment cost parameter γ oscillates around zero in the early periods and substantially increases from mid-2000s (column 2). Taken together, the estimation results based on the Euler equation support Hypothesis 2 that it is an upward trend of capital adjustment costs that results in the decreasing pattern of I-CF sensitivity.

C. Evidence Based on Structural Estimation of Parameters

To build on the analysis of Sections III, IV.A, and IV.B, we estimate relevant model parameters using the SMM approach. SMM not only bypasses the need for using a proxy for q but also avoids relying on instruments, which are required for the estimation of the Euler equation. The objective here is to identify the values of key parameters, γ and b, that would result in matching relevant properties of the actual data, that is, the coefficients of the baseline regression (1). Hence, for each 5-year period, we estimate γ and b by matching the actual moments with the moments generated from the simulated data. The moments we match are the q sensitivity of investment, β_1, and cash flow sensitivity of investment, β_2. The details of the estimation procedure and the adopted remaining parameter values are presented in the Appendix.

The estimation output is reported in Table 5. The magnitude of estimated adjustment cost parameter γ in 1977–1981 of 0.477 implies that the average firm incurs

TABLE 5

Parameter Estimation Results Based on the SMM for Each Subsample Period

Table 5 reports that β_1 is the q sensitivity of investment and β_2 is the cash flow sensitivity of investment, as in baseline regression (1). Columns 2 and 3 (4 and 5) show β_1 and β_2 calculated based on the actual (simulated) data in each subsample period. Columns 6 and 7 report the estimated model parameters γ and b that minimize the weighted distance between the actual and simulated moments.

	Actual Moments		Simulated Moments		Parameter Estimates	
Period	β_1	β_2	β_1	β_2	γ	b
1977–1981	0.021	0.271	0.028	0.280	0.477	0.698
1982–1986	0.022	0.131	0.020	0.150	0.829	0.692
1987–1991	0.016	0.058	0.007	0.074	1.220	0.671
1992–1996	0.010	0.046	0.006	0.068	1.583	0.647
1997–2001	0.007	0.022	0.002	0.056	1.373	0.657
2002–2006	0.006	0.005	0.001	0.001	6.617	0.507
2007–2011	0.007	0.000	0.003	−0.001	3.914	0.734
2012–2016	0.004	−0.002	0.004	−0.001	2.748	0.727
2017–2019	0.003	−0.004	0.004	−0.001	2.748	0.672

an adjustment cost of approximately \$0.137 (with the mean value of investment in 1977–1981 equal to 0.287) for the marginal \$1 of investment expenditure.[19] In other words, adjustment costs constitute approximately one eighth (i.e., $0.137/1.137 = 12\%$) of the total investment costs, which is consistent with Barnett and Sakellaris (1999). Furthermore, our estimates of γ before 2000 (i.e., ranging from 0.477 to 1.583) are in line with findings of Nikolov and Whited (2014) (i.e., γ between 0.5 and 1.3), DeAngelo et al. (2011) (i.e., 0.152) and Gao et al. (2021) (i.e., 0.939). Importantly, it can be seen that the capital adjustment cost parameter estimated with the simulated method of moments displays an increasing time trend, which is consistent with our previous findings. It further illustrates that the increasing pattern of capital adjustment costs is robust to using a different estimation methodology.

V. Adjustment Costs as a Function of Knowledge Capital

Having explored the consequences of (increasing) capital adjustment costs, we now look at the antecedents of those costs. The innovation of technology has evolved significantly over the past 40 years. According to McKinsey & Company (2017), manufacturing organizations have entered a new era with advances in automation, robotics, and artificial intelligence that necessitate the adoption, integration, and development of the technology into business solutions, which enhances the associated cost of time for labor to retrain into the highly skilled positions.

Extant academic literature offers similar insights referring to the technological progress or knowledge advancement as a significant contributor to the increase of capital adjustment costs. Klette and Kortum (2004) define knowledge capital as the "skills, techniques, and know-how that [a firm] draws on as it attempts to innovate." The development of knowledge capital is associated with the frequent use of intellectual property or the reliance on skilled scientists or engineers, which can

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[19] Since $\$0.287 \times 0.477$ is \$0.137.

add to the labor expenses (Belo, Li, Lin, and Zhao (2017)), costs and complexity of installing machinery and equipment or opening a new plant.[20] Bloom and Van Reenen (2002) postulate that the reason for the sluggish impact of patents on market value is that the new processes have to be embodied in the new capital equipment and training. With the growing adoption of new technologies, firms need to reorient their investments or retrofit their existing plants toward technology-intensive plants or equipment.[21] The tendency to adopt new technologies can be captured by the stock of knowledge capital, thus one would naturally expect that capital adjustment costs increase with the latter. Using industry-level evidence, Hornstein and Krusell (1996) and Greenwood and Yorukoglu (1997) suggest that technological improvement can cause productivity slowdown as the installation of new capital goods results in high costs of learning. Kiley (2001) presents evidence of substantial costs associated with training and maintaining information technology, while Bessen (2002) attributes increasing adjustment costs to an increase in spending on information technology (e.g., customization of software). Groth (2008) estimates that it is particularly costly to install capital in ICT-intensive industries (see also Bessen (2002), who reports high adjustment cost estimates for high-tech industries). Uchida, Takeda, and Shirai (2012) identify significant costs of capital adjustment for the sectors that have undergone a technological change in automobile electronics.

The rate of technology growth has been significant (Jorgenson and Stiroh (2000), Oliner and Sichel (2000)). We show evidence of the associated increase in the knowledge capital intensity, measured as the ratio of intangible capital stock to total assets, in Panel A of Table 6. We use the proxy for the value of intangible capital stock based on Peters and Taylor (2017), which comprises spending (current and past) in both R&D (research and development) and organization capital (e.g., advertising, payments on strategy consults and employee training) capitalized using the perpetual inventory method.[22] The mean (median) level of knowledge capital intensity, N_{it}, increases from 0.454 (0.405) in 1977–1981 to 0.814 (0.654) in 2012–2016. The gradual growth of the firm-level intensity of knowledge capital translates into increasing costs associated with installing complex machine systems, employee training and recruitment fees for skilled talent.

In the remainder of this section, we explore the relationship between I-CF and I-q sensitivities and knowledge capital, analyze the link between the scaling parameter γ of the adjustment cost function and knowledge capital using the Euler equation framework, and estimate parameters describing the dynamics of knowledge capital (and adjustment costs) using an extension of the intertemporal investment model of Section IV.[23]

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[20] Examples of those installation costs include longer time in setting up complex machine systems, employee training (and the associated lost in production) for digital transformation on the equipment, advertising, search, and selection fees for skilled workers.

[21] For instance, Gurbaxani (1992) notes that the stock of information technology capital accounts for a rapidly growing share of total U.S. capital stock.

[22] Note that Peters and Taylor's (2017) data for intangible capital is available until 2017, which is reflected in the length of our sample period in this part of the analysis.

[23] In Appendix OA3 of the Supplementary Material, we further corroborate the existence of the relationship between I-CF sensitivity and knowledge capital using regression analysis that exploits the cross-country and cross-industry variation of the latter.

TABLE 6

Summary Statistics and Investment Regression with the Interaction of Intangible Capital

Panel A of Table 6 shows the summary statistics of N_{it}, which is defined as the ratio of intangible capital (based on Peters and Taylor (2017)) to total assets. Panel B displays the regression output by interacting cash flow and q variables with N_{it} for both OLS estimator with firm and year-fixed effects (models 1 and 2) and GMM5 estimator (models 3 and 4). ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

Panel A. Summary Statistics of N_{it}

Period	Mean	Std. Dev.	$p(25)$	$p(50)$	$p(75)$	Serial Corr.
1977–1981	0.454	0.272	0.264	0.405	0.587	0.961
1982–1986	0.507	0.322	0.285	0.447	0.651	0.944
1987–1991	0.566	0.406	0.297	0.481	0.722	0.929
1992–1996	0.601	0.432	0.312	0.510	0.768	0.940
1997–2001	0.693	0.647	0.337	0.539	0.810	0.892
2002–2006	0.797	0.686	0.410	0.637	0.923	0.927
2007–2011	0.856	0.864	0.395	0.661	0.973	0.912
2012–2016	0.814	0.740	0.393	0.654	0.955	0.946

Panel B. Regressions with the Interaction with N_{it}

	OLS	OLS	GMM5	GMM5
Dependent Variable	$\frac{I_{it}}{K_{it}}$ 1	$\frac{I_{it}}{K_{it}}$ 2	$\frac{I_{it}}{K_{it}}$ 3	$\frac{I_{it}}{K_{it}}$ 4
Q_{it}	0.007*** (0.000)	0.016*** (0.001)	0.012*** (0.001)	0.008*** (0.000)
$\frac{CF_{it}}{K_{it}}$	0.029*** (0.002)	0.093*** (0.006)	0.012*** (0.002)	0.021*** (0.002)
$Q_{it} \times N_{it}$	−0.002*** (0.000)	−0.001*** (0.000)	−0.001*** (0.001)	−0.001*** (0.000)
$\frac{CF_{it}}{K_{it}} \times N_{it}$	−0.013*** (0.001)	−0.008*** (0.001)	−0.005*** (0.002)	−0.005*** (0.001)
N_{it}	−0.092*** (0.005)	−0.084*** (0.004)	−0.110*** (0.005)	−0.086*** (0.004)
$Q_{it} \times$ TREND		−0.001*** (0.000)		−0.0001** (0.000)
$\frac{CF_{it}}{K_{it}} \times$ TREND		−0.011*** (0.001)		−0.000 (0.000)
TREND				−0.019*** (0.001)
Constant	0.272*** (0.003)	0.256*** (0.003)	0.001*** (0.000)	0.006*** (0.001)
No. of Obs.	61,079	61,079	61,079	61,079
R^2 (OLS)/J (GMM5)	0.113	0.138	69.553	140.022

A. I-CF Regression with the Interaction of Knowledge Capital

We now provide an initial examination of the effect of knowledge capital on capital adjustment costs and, subsequently, I-CF sensitivity. We interact cash flow and q variables with knowledge capital intensity (N_{it}) using an extended version of the baseline regression (1) estimated for the full sample. If capital adjustment costs, which increase with the intensity of knowledge capital, do bring down I-CF sensitivity, one would also expect N_{it} to be negatively related to I-CF sensitivity. In Panel B of Table 6, we report the results based on the OLS estimator with firm and year-fixed effects (models 1 and 2) and those based on GMM5 (Erickson and Whited (2000), (2002)) and EW estimators (models 3 and 4). For models 1 and 3, the coefficients of $\frac{CF_{it}}{K_{it}} \times N_{it}$ and $Q_{it} \times N_{it}$ are negative and statistically significant

TABLE 7

Parameter Estimation Results Based on the Euler Equation with Parameterized Adjustment Costs

Table 7 shows the 2-step GMM estimation results with parameterized γ_{it}. Standard errors (S.E.) clustered at firm level for the estimates are reported. ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

Panel A. Parameter Estimates

	d_0	d_1	b
Estimates	−10.683***	21.572***	0.000
S.E.	1.688	2.868	4.239

for both estimators. The results indicate that knowledge capital has a negative effect on both I-CF and I-q sensitivity. The finding is therefore consistent with the view that capital adjustment costs, which stem from investment in knowledge capital, contribute to a lower sensitivity of investment to cash flow and q. To further show that the knowledge capital N_{it}, despite increasing over time, captures more than the time-series variation of macroeconomic trends, we additionally control for the interaction term of cash flow and q variables with TREND in models 2 and 4. The coefficients of $\frac{\mathrm{CF}_{it}}{K_{it}} \times N_{it}$ and $Q_{it} \times N_{it}$ continue to be negative and statistically significant, indicating that the negative effect of N_{it} on I-CF and I-q sensitivity is robust to controlling for the time trend.

B. Parametrization of the Adjustment Cost in Euler Equation

We further investigate the relation between capital adjustment costs and knowledge capital using the Euler equation framework, with adjustment cost parameter γ being now a function of knowledge capital intensity. We adopt a similar approach to Whited and Wu (2006) and parameterize γ_{it} as a linear function of N_{it}, that is, we set $\gamma_{it}(N_{it}) = d_0 + d_1 N_{it}$. We then substitute the expression for γ_{it} into equation (6) and, otherwise, repeat the estimation procedure of Section IV.B for the parameter set $[d_0 d_1 b]$. The GMM estimation results are presented in Table 7. In Figure 1, we plot the evolution of γ_t as a function of N_t, defined as the average value of N_{it} across all firms in year t, based on the estimated parameters d_0 and d_1. The results show that the parameter estimate of d_1 is positive and significant at the 1% level, indicating that γ_{it} and, more generally, capital adjustment costs are positively associated with N_{it}. The time-series evolution of predicted γ_t implies that the capital adjustment costs increase over time, which is driven by the increasing trend of N_t.

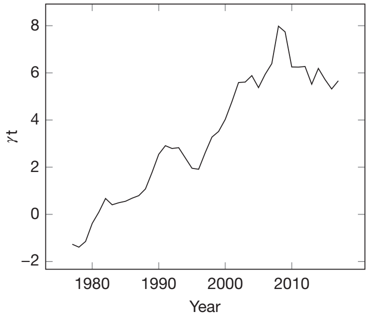
C. Endogenizing Adjustment Cost in a Fully Dynamic Framework

We next derive foundations of capital adjustment costs by endogenizing the adjustment cost parameter in an investment model. We subsequently estimate model parameters using the SMM approach. In this framework, the firm valuation is summarized by three state variables: firm-level profitability shock A, knowledge

FIGURE 1

Evolution of Predicted γ_t

Figure 1 plots the time-series evolution of predicted γ_t based on the parameter estimates of d_0 and d_1 from Table 7.



capital stock N, and physical capital stock K. Managers choose investment in both knowledge capital n and physical capital I to maximize firm value:

$$V(A,K,N) = \max_{I,n}[(\Pi(A,K,N) - I - n1_{n>0} - G(I,K,\gamma(N')) - H(X,K)) + \vartheta E_{\{A'|A\}} V(A',K',N')], \tag{7}$$

with the indicator function used to reflect irreversibility of knowledge capital investment. Profit is modeled with a constant elasticity of substitution (CES) function (cf. Belo et al. (2017)), $\Pi(A,K,N) = A\left(\kappa K^{1-1/\theta} + (1-\kappa)N^{1-1/\theta}\right)^{\alpha/(1-1/\theta)}$, where $\kappa > 0$ represents the relative weight of the two inputs in the production process, α is the degree of returns to scale, and θ is the elasticity of substitution between physical capital and knowledge capital.[24] Investment in knowledge capital in a given period is denoted by n and its depreciation rate, which captures gradual knowledge obsolescence and spillovers, is δ_N. The law of motion of N is given by $N' = n + (1-\delta_N)N$. The capital adjustment cost parameter is a function of knowledge capital and is expressed as $\gamma(N) = c_0 + c_1 N$. Other parameters and variables are as defined in Section IV.C (see also the Appendix). We repeat the steps of the structural estimation procedure of that section but augmented with an additional choice variable n. We now estimate an extended set of parameters, that is, $[c_0\, c_1\, \delta_N\, b\, \alpha\, \kappa\, \theta\, \rho_a\, \sigma_a]$, to match as closely as possible the empirical time-series pattern of I-CF sensitivity. The estimates are reported in Table 8.

The simulated process for the capital adjustment cost parameter and time-series trend of I-CF sensitivities are shown in Figure 2. Again, after closely matching the pattern of I-CF sensitivity, endogenized $\gamma(N)$ demonstrates an increasing trend as a result of the upward evolution of N over time. The SMM estimation results again support our argument that the declining I-CF sensitivity is driven by increasing capital adjustment costs, which is a product of accumulating the knowledge capital stock.

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[24] The CES function collapses to a Cobb–Douglas function when $\theta \to 1$.

TABLE 8

Parameter Estimation Results Based on the SMM with Endogenized $\gamma(N)$

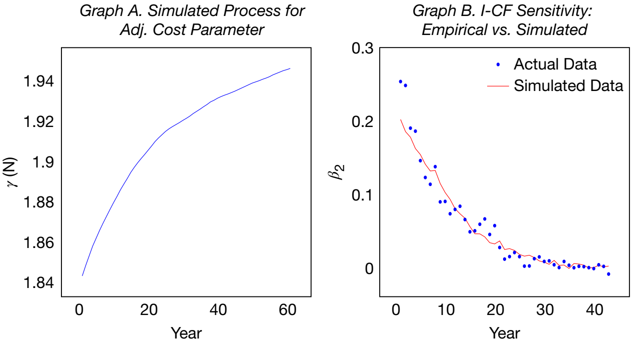
Table 8 reports the estimated structural parameters of the slope and intercept of the adjustment cost function of knowledge capital, as well as the estimates of depreciation rate, financing costs, returns to scale, weight of physical capital, elasticity of substitution, the mean reversion coefficient and volatility of productivity, based on the dynamic model of the firm given by equation (7).

Parameters of Capital Adjustment Costs		
Intercept	c_0	0.605
Slope	c_1	0.124
Other parameters:		
Depreciation rate	δ_N	0.036
Financing cost	b	0.408
Returns to scale	α	0.633
Weight of physical capital	κ	0.540
Elasticity of substitution	$1-1/\theta$	−0.508
Mean reversion coefficient of productivity	ρ_a	0.880
Volatility of productivity	σ_a	0.051

FIGURE 2

Simulated Process of γ and Estimated β_2

Graph A of Figure 2 shows the evolution of the endogenized adjustment costs parameter $\gamma(N)$ expressed as a function of $\gamma(N)=c_0+c_1N$. In Graph B, the solid line plots the time-series evolution of the simulated I-CF sensitivity based on data simulated using parameters from Table 8, whereas the dots illustrate the empirical I-CF sensitivity based on the actual data.


Graph A. Simulated Process for Adj. Cost Parameter

Graph B. I-CF Sensitivity: Empirical vs. Simulated

VI. Conclusions

The gradual decline of I-CF sensitivity over time is a phenomenon that has remained largely unexplained in the extant literature. By focusing on two key factors inspired by a neoclassical investment framework with costly external financing: financial frictions and capital adjustment costs, we provide evidence that goes toward settling the ongoing debate. To evaluate whether either of those factors contribute to the declining pattern of I-CF sensitivity, we use a broad range of tests ranging from a nonlinear estimation of the first-order condition, a GMM estimation of the Euler equation, to the structural estimation of the parameters capturing financial and real frictions.

We demonstrate that while I-CF sensitivity is a function of both financial constraints and capital adjustment costs, it is the evolution of the latter that is largely capable of explaining the declining I-CF sensitivity pattern. As firms need to divide financial resources earmarked for investment between covering actual investment expenditure and capital adjustment costs, higher adjustment costs lead to a lower sensitivity of investment to available cash flow. Our estimates unequivocally show that capital adjustment costs exhibit an upward time trend, which explains why I-CF sensitivity has declined over time. The gradual increase of capital adjustment costs is also consistent with the documented decrease in I-q sensitivity.

In line with several recent contributions, we do not find evidence of a variation in the magnitude of financing frictions that would be consistent with the observed I-CF sensitivity pattern. (The hypothesis of a decline in the magnitude of financing constraints is not supported by the observed negative trend in I-q sensitivity either.)

We also provide a microfounded explanation of the capital adjustment cost increase, based on the accumulation of knowledge capital in response to expanding new product markets and technological progress. While such investment translates into firms' higher productivity, it also leads to increased adjustment costs.

More generally, our results demonstrate that I-CF sensitivity should be interpreted as a joint measure of financial and *real* frictions. This observation has implications for the design and interpretation of empirical tests of financing constraints that rely on using I-CF sensitivity. Namely, a lower sensitivity of investment to cash flow may be symptomatic of a higher cost of adjusting capital stock rather than of an improved access to external financing.

Appendix. Details of the Structural Estimation Approach

Denote (A,K) as the state of the firm, the value of which is maximized. The productivity shock A is the only source of economic uncertainty. Numerical solutions for the firm value and level of investment are based on the iterative value iteration algorithm. To simplify notation, denote x_t as x and x_{t+1} as x' (the analogous notation is applied to all other variables). The logarithm of the shock variable, denoted as $a=\log(A)$, is assumed to follow a first-order autoregressive process with zero drift:$a'=\rho_a a+\varepsilon'$, where ρ_a is the autoregressive coefficient and $\varepsilon'\sim N(0,\sigma_a)$ is identically independently distributed across time. We transform the first-order autoregressive process into a discrete-state Markov chain following Tauchen (1986) where the value sets and corresponding transition probability are determined by $[\rho_a\sigma_a]$. We let a take $N_a=10$ points from the discretized set of $\left[-3\sigma_a/\sqrt{\left(1-\rho_a^2\right)}\ \ 3\sigma_a/\sqrt{\left(1-\rho_a^2\right)}\right]$ and define the interval between each point as $w=6\sigma_a/\left(\sqrt{\left(1-\rho_a^2\right)}(N_a-1)\right)$. We denote the probability that the log stochastic shock a' becomes $\overline{a}_i$ given that the log stochastic variable in the last period a is $\overline{a}_j$ as $p(j,i)=\Pr\left[a'=\overline{a}_i|a=\overline{a}_j\right]$. Then the probability matrix for $j=1\ldots N_a$ and $i=1\ldots N_a$ is

$$\text{(A-1)}\qquad \begin{aligned} p(j,i) &= \Pr\left[\overline{a}_i-w/2\leq\rho_a\overline{a}_j+\varepsilon'\leq\overline{a}_i+w/2\right] \\ &= N\left(\frac{\overline{a}_i-\rho_a\overline{a}_j+w/2}{\sigma_a}\right)-N\left(\frac{\overline{a}_i-\rho_a\overline{a}_j-w/2}{\sigma_a}\right). \end{aligned}$$

The discretized set for capital stock K is defined as $\overline{K},\overline{K}(1-\delta),\ldots,\overline{K}(1-\delta)^{49}$, where the maximum value of capital $\overline{K}$ is determined by $\Pi\left(\overline{A},\overline{K}\right)=\delta\overline{K}$ where the profit function is $\Pi(A,K) = AK^{\alpha}$ (see Gomes (2001)). Remaining parameters broadly follow Gomes (2001) and Hennessy and Whited (2007): the curvature of the profit function α is 0.45, the autocorrelation coefficient of the stochastic profit component ρ_a is 0.65, its volatility σ_a is 0.15, the depreciation rate δ is 0.15 and risk-free rate r equals 0.05.

Now, for a given set of parameters $\Theta = [\gamma b]$, we solve for the value function and the optimal policy function. The goal is to identify the parameters that match the actual data moments, denoted as M_d, with simulated moments, denoted as $m_s(\Theta)$. The parameter estimates are therefore chosen to minimize the weighted distance between actual moments and simulated moments:

$$\widehat{\Theta} = \arg\min\nolimits_{\Theta}\left[M_d - \frac{1}{S}\sum_{s=1}^{S} m_s(\Theta)\right] W \left[M_d - \frac{1}{S}\sum_{s=1}^{S} m_s(\Theta)\right], \tag{A-2}$$

where W is the optimal weighting matrix, which is given by the inverse of the variance–covariance matrix of M_d. We create $S = 6$ artificial panels containing 1,000 firms (paths) with 40 time periods. For each path, the log state variable a is restricted to the discretized set of values. We simulate 60 periods for each firm and drop the first 20 periods to allow the firms to move away from a possibly suboptimal starting point (see Hennessy and Whited (2005)). At the end of each panel, we run the baseline regression of investment on q and cash flow. Finally, we take the average of the cash flow coefficients and q coefficients over the S panels and form the simulated moments.

Supplementary Material

To view supplementary material for this article, please visit http://doi.org/10.1017/S0022109023000418.

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