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.

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1 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 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; 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), Moyen (2004), Alti (2003), and Gomes (2001). 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 Bond and Cummins, 2001; Cummins et al., 2006; Ağca and Mozumdar, 2017, among many others). 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., Chen et al., 2007;

Gilchrist and Himmelberg, 1995). 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 et al. (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 (De Loecker et al., 2020; Grullon et al., 2019) should lead, if anything, to an upward (rather than the observed downward) trend.

In this paper, we use a neoclassical investment model with costly external financing to

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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.

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 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 four 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 non-overlapping 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.

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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 3.

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 adjustment cost parameters based on the first-order condition which has Tobin's

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[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.

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

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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 Riddick and Whited (2009) and Gamba and Triantis (2008).

[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 to 12 months to complete” and SEAT’s (the Spanish subsidiary of the Volkswagen Group) re-skilling program opens the possibility for employees to retrain during working hours.

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 4 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 paper 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 Abel and Eberly (2002), Barnett and Sakellaris (1998, 1999), Basu et al. (2003), Cooper and Haltiwanger (2006), Caggese (2007), Groth and Khan (2010), Pratap (2003) and Whited (1998).[7] Also, while investment is reliant on 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.

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[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 UK.

2 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 ($csho \times prcc$), 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, that is I/K, Q, and CF/K, are required to have non-missing values for each observation. Following Almeida et al. (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) and 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

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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 2007-09 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).

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 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 1977-81 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 et al., 2010; Erickson and Whited, 2012).

The baseline OLS regression equation for investment is

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

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

TABLE 1
Summary statistics for regression variables

Mean, standard deviation, percentiles and first-order serial correlation ρ_k for variable $k \in \{I/K, Q, CF/K\}$ for each subsample period (1977-1981 through 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 U.S. for which relevant data is available in Compustat over 1977-2019 period.

Period:	1977-81	1982-86	1987-91	1992-96	1997-01	2002-06	2007-11	2012-16	2017-19
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
$\rho_{CF/K}$	0.754	0.687	0.627	0.627	0.627	0.692	0.651	0.729	0.795

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 periods and from 2002-2006 onwards becomes non-significant, 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 $Q_{it} \times Trend$ and $\frac{CF_{it}}{K_{it}} \times Trend$ are negative and, therefore, confirm the results of the subsample analysis.

In Section 3 below, 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.

3 Capital adjustment costs and I-CF sensitivity

The extant literature on investment-cash flow 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,

TABLE 2
Baseline linear regression results

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% level, respectively.

Panel A. Estimation results per subsample period

Period	OLS		GMM5		
	β_1	β_2	β_1	β_2	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}	$\frac{CF_{it}}{K_{it}}$	$Q_{it} \times Trend$	$\frac{CF_{it}}{K_{it}} \times Trend$	$Trend$
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)

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 et al. (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 re-purposing 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:

H1: *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

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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 optimise 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".

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 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:

H2: *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., H2) that decreasing I-CF sensitivity is driven by rising capital adjustment costs.

4 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 4 and 5 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 set-up, 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. 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

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

rate. The assumed convex adjustment costs incentivize firms to smooth investment, which results in only a partial adjustment of capital towards its desired level, and leads to positive serial correlation of investment (see, e.g., Chen et al., 2022; Cooper et al., 1999; Caballero and Engel, 2003; Fiori, 2012). The demonstrated evidence of the presence of convex adjustment costs (e.g., Cao et al., 2019; Hayashi, 1982; Kogan, 2004) 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 one if $I \geq \Pi$ and zero 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.

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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.

Equityholders choose an investment policy to maximize the firm value:

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

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:

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

Eq. (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.

4.1 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

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

where η_j is dummy variable for each two-digit SIC industry code and ξ_t represents the year fixed effect.[13] Other variables are as those described in Section 2. Estimated parameters are all expected to be positive (and are, therefore, restricted to non-negative 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 1977-1981, 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 eq. (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

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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, 10%-17% of firms have only a single observation and approx. 30% – two years observations in the subsample period.

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 H1 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. Our result therefore echoes the conclusion in 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 1952-1978).[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 et al., 2011;

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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 non-convex 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 $\$\gamma I/K$.

Gao et al., 2021; Nikolov and Whited, 2014). 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., Barnett and Sakellaris, 1999; Gilchrist and Himmelberg, 1995; Lewellen and Lewellen, 2016; Nikolov and Whited, 2014) 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 et al., 2020) and the fundamental q (Campello and Graham, 2013; Goyal and Yamada, 2001).[17]

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[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 ($\hat{Q}$) 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 $q = \hat{Q}(1 + \hat{a_2} + 2\hat{a_4} \log(K) + \hat{a_5} \log(A))$. 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.

TABLE 3

Estimation results based on the q equation

Estimation results in Panel A is based on eq. (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 Panel A and Panel B is one 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% level, respectively.

Panel A: Estimation of q equation with Tobin's q						Panel B: Estimation of q equation with alternative measures of q							
						Gala et al.'s marginal q:				Fundamental q:			
Period	γ	ψ	b	R^2	$t(\psi = 2)$	Period	γ	b	R^2	Period	γ	b	R^2
1977-1981	2.701***	2.150***	0.000	0.214	1.620	1977-1981	0.029	0.000	0.038	1977-1981	1.072***	0.000	0.123
	(0.353)	(0.093)	(0.250)				(0.231)	(0.152)			(0.370)	(0.155)	
1982-1986	5.570***	1.970***	0.250	0.224	-0.549	1982-1986	0.200	0.133	0.032	1982-1986	1.468**	0.000	0.126
	(0.159)	(0.054)	(0.191)				(0.392)	(0.486)			(0.783)	(0.880)	
1987-1991	6.726***	2.165***	1.141***	0.168	1.381	1987-1991	0.348	0.179	0.002	1987-1991	2.374**	0.000	0.121
	(0.670)	(0.119)	(0.378)				(0.397)	(0.439)			(0.943)	(1.401)	
1992-1996	13.119***	2.004***	2.502***	0.261	0.035	1992-1996	0.823	0.486	0.005	1992-1996	4.005**	0.000	0.164
	(1.279)	(0.121)	(0.685)				(1.126)	(0.714)			(2.307)	(1.189)	
1997-2001	17.958***	1.853***	2.149***	0.246	-3.181^{***}	1997-2001	1.451	0.073	0.117	1997-2001	3.599	0.220	0.110
	(0.659)	(0.046)	(0.515)				(1.388)	(0.113)			(3.583)	(0.406)	
2002-2006	30.513***	2.117***	2.700***	0.333	5.118***	2002-2006	2.493*	0.217	0.006	2002-2006	9.014**	0.031	0.125
	(1.592)	(0.023)	(0.168)				(1.736)	(0.294)			(4.408)	(0.400)	
2007-2011	27.520	2.179***	2.520***	0.313	1.973**	2007-2011	3.813*	0.209	0.079	2007-2011	10.037**	0.966	0.208
	(1.503)	(0.091)	(0.997)				(2.188)	(0.196)			(4.552)	(1.048)	
2012-2016	33.959***	2.116***	3.400***	0.367	1.218	2012-2016	4.213*	0.148	0.163	2012-2016	10.646**	1.015	0.178
	(1.351)	(0.095)	(0.478)				(2.338)	(0.177)			(5.533)	(1.170)	
2017-2019	43.026***	1.719***	2.709***	0.315	2.026**	2017-2019	6.291***	0.195	0.079	2017-2019	8.572***	0.709	0.174
	(3.740)	(0.139)	(0.344)				(2.160)	(0.105)			(4.984)	(0.950)	

The results with Gala et al.'s q (reported on the left-hand side of Panel B) 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.

4.2 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 et al., 2010). To perform the estimation, we first express the maximization problem (2) as

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

subject to $K_{\tau+1} = I_\tau + (1-\delta)K_\tau$. The right-hand side of eq. (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 $E_t(\epsilon_{t+1}) = 0$, to remove the expectation operator (details are presented in Online Appendix OA2), we arrive at the estimation equation for the Euler equation:

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

We follow Whited (1998) and employ two-step GMM to estimate the parameters in (6). As information set at time t is orthogonal to the error at time $t+1$, we use moment condition $E(Z_t \epsilon_{t+1}) = 0$, 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 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

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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

Two-step GMM estimation results of eq. (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% level, respectively.

Period	γ	b	J statistic
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)

support hypothesis H2 that it is an upward trend of capital adjustment costs that results in the decreasing pattern of I-CF sensitivity.

4.3 Evidence based on structural estimation of parameters

To build on the analysis of Sections 3 and 4.1-4.2, 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 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.

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

TABLE 5
Parameter estimation results based on the SMM for each subsample period

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

5 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 add to the labor expenses (Belo et al., 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 towards 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 (Oliner and Sichel, 2000; Jorgenson

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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) note that the stock of information technology capital accounts for a rapidly growing share of total U.S. capital stock.

and Stiroh, 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 4.[23]

5.1 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)

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[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 Online Appendix OA3, 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

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Panel A 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).

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}

	(1)	(2)	(3)	(4)
	OLS	OLS	GMM5	GMM5
Dependent variable:	$\frac{I_{it}}{K_{it}}$	$\frac{I_{it}}{K_{it}}$	$\frac{I_{it}}{K_{it}}$	$\frac{I_{it}}{K_{it}}$
Q_{it}	0.007^{***}	0.016^{***}	0.012^{***}	0.008^{***}
	(0.000)	(0.001)	(0.001)	(0.000)
$\frac{CF_{it}}{K_{it}}$	0.029^{***}	0.093^{***}	0.012^{***}	0.021^{***}
	(0.002)	(0.006)	(0.002)	(0.002)
$Q_{it} \times N_{it}$	-0.002^{***}	-0.001^{***}	-0.001^{***}	-0.001^{***}
	(0.000)	(0.000)	(0.001)	(0.000)
$\frac{CF_{it}}{K_{it}} \times N_{it}$	-0.013^{***}	-0.008^{***}	-0.005^{***}	-0.005^{***}
	(0.001)	(0.001)	(0.002)	(0.001)
N_{it}	-0.092^{***}	-0.084^{***}	-0.110^{***}	-0.086^{***}
	(0.005)	(0.004)	(0.005)	(0.004)
$Q_{it} \times Trend$		-0.001^{***}		-0.0001^{**}
		(0.000)		(0.000)
$\frac{CF_{it}}{K_{it}} \times Trend$		-0.011^{***}		-0.000
		(0.001)		(0.000)
$Trend$				-0.019^{***}
				(0.001)
Constant	0.272^{***}	0.256^{***}	0.001^{***}	0.006^{***}
	(0.003)	(0.003)	(0.000)	(0.001)
Obs.	61,079	61,079	61,079	61,079
R^2 (OLS)/J (GMM5)	0.113	0.138	69.553	140.022

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 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 $\frac{CF_{it}}{K_{it}} \times N_{it}$ 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.

5.2 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 eq. (6) and, otherwise, repeat the estimation procedure of Section 4.2 for the parameter set $[d_0\ d_1\ b]$. The GMM estimation results are presented in Panel A of Table 7. In Panel B, 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.

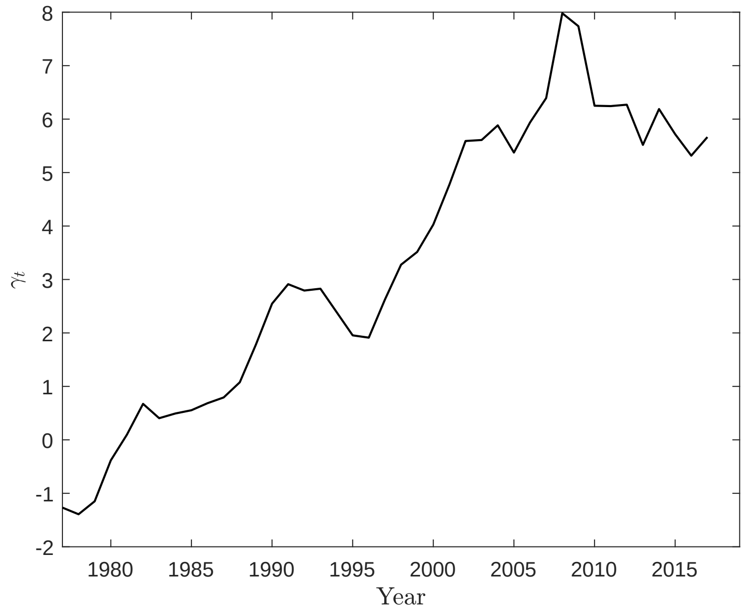
TABLE 7
Parameter estimation results based on the Euler equation with parameterized adjustment costs

Panel A shows the two-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% level respectively. Panel B plots the time-series evolution of predicted γ_t based on the parameter estimates of d_0 and d_1 from Panel A.

Panel A. Parameter estimates

	d_0	d_1	b
Estimates	-10.683^{***}	21.572^{***}	0.000
S.E.	1.688	2.868	4.239

Panel B. Evolution of predicted γ_t



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

$$V(A,K,N) = \max_{I,n}[(\Pi(A,K,N) - I - n\mathbf{1}_{n>0} - G(I,K,\gamma(N^{'})) - H(X,K)) + \vartheta E_{\{A^{'}|A\}}V(A^{'},K^{'},N^{'})], \tag{7}$$

with the indicator function used to reflect irreversibility of knowledge capital investment. Profit is modelled with a constant elasticity of substitution (CES) function (cf. Belo et al., 2017), $\Pi(A,K,N) = A(\kappa K^{1-1/\theta} + (1-\kappa)N^{1-1/\theta})^{\alpha/(1-1/\theta)}$, 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 4.3 (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

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

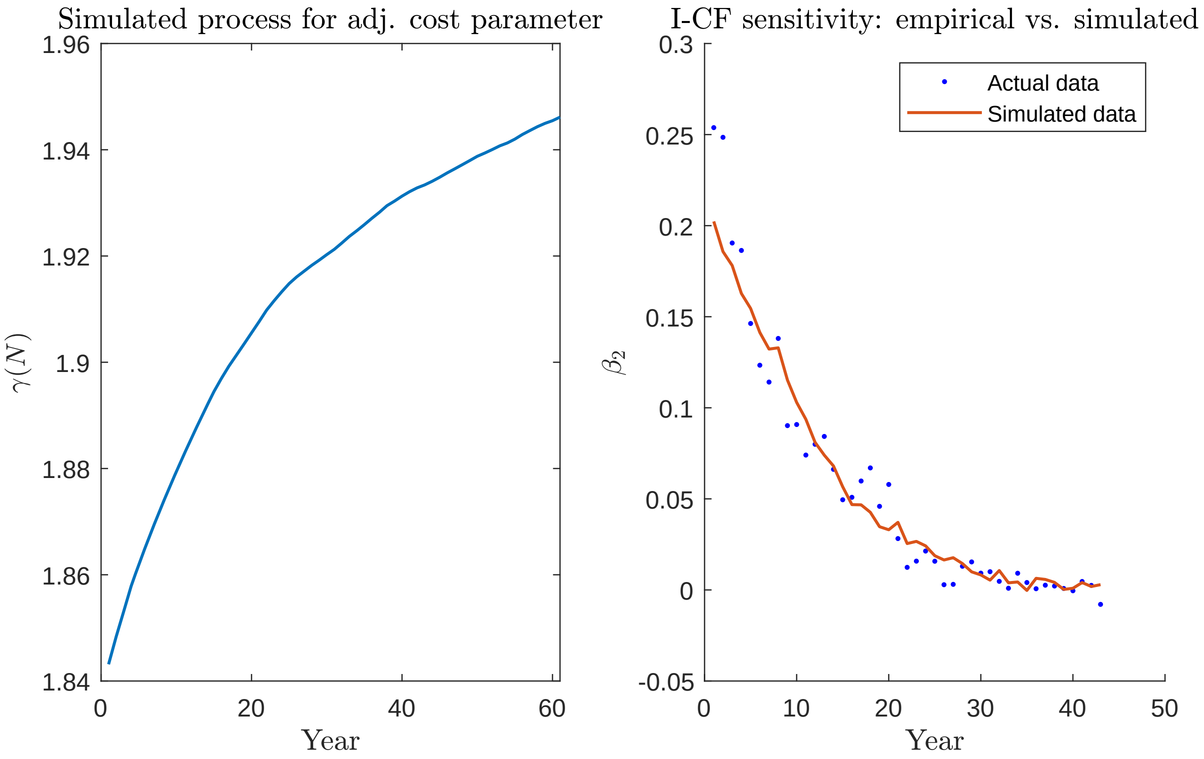
closely as possible the empirical time-series pattern of investment-cash flow sensitivity. The estimates are reported in Table 8.

TABLE 8
Parameter estimation results based on the SMM with endogenized $\gamma(N)$

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

The simulated process for the capital adjustment cost parameter and time-series trend of I-CF sensitivities are shown in Figure 1. Again, after closely matching the pattern of investment-cash flow 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 investment-cash flow sensitivity is driven by increasing capital adjustment costs, which is a product of accumulating the knowledge capital stock.

FIGURE 1
Simulated process of $\gamma(N)$ and estimated β_2



6 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 towards 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: $a^{'} = \rho_a a + \epsilon^{'}$, where ρ_a is the autoregressive coefficient and $\epsilon^{'} \sim N(0, \sigma_a)$ 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 $[-3\sigma_a/\sqrt{(1-\rho_a^2)} \quad 3\sigma_a/\sqrt{(1-\rho_a^2)}]$ and define the interval between each point as $w = 6\sigma_a/(\sqrt{(1-\rho_a^2)}(N_a - 1))$. We denote the probability that the log stochastic shock $a^{'}$ becomes $\bar{a}_i$ given that the log stochastic variable in the last period a is $\bar{a}_j$ as $p(j,i) = \Pr[a^{'} = \bar{a}_i | a = \bar{a}_j]$. Then the probability matrix for $j = 1 \ldots N_a$ and $i = 1 \ldots N_a$ is

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

The discretized set for capital stock K is defined as $\bar{K}, \bar{K}(1-\delta), \ldots, \bar{K}(1-\delta)^{49}$, where the maximum value of capital $\bar{K}$ is determined by $\Pi(\bar{A}, \bar{K}) = \delta \bar{K}$ 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:

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

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 1000 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.

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Online Appendix

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

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Abstract

This Online Appendix contains results and technical details that are referred to but not reported in detail in the main manuscript. In Section OA1, we demonstrate the derivation of the empirical counterpart of the Euler investment equation, whereas the evidence regarding the increase in the adjustment costs based on industry-level data is presented in Section OA2. Section OA3 contains a firm-level data analysis of the differences in the evolution of I-CF sensitivity between developed and developing countries as well as between high-tech and non high-tech firms, in which the cross-sectional variation of the levels of knowledge capital stock is exploited.

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OA 1 Euler equation: Empirical counterpart

The empirical counterpart of the Euler investment equation is derived as follows. The firm aims to maximize the expected discounted value of the net profit stream:

$$V(A_t, K_t) = \max_{\{K_{\tau+1}, I_\tau\}_{\tau=t}^{\infty}} E_t \sum_{\tau=t} \left(\frac{1}{1+r}\right)^{\tau-t} [\Pi(A_\tau, K_\tau) - I_\tau - G(I_\tau, K_\tau) - H(X_\tau, K_\tau)], \tag{OA 1.1}$$

subject to $I_t = K_{t+1} - (1-\delta)K_t$. All functions are as previously defined. The Lagrangian with multiplier q_τ is given by

$$\begin{aligned} \mathcal{L} \;=\; & \max_{\{K_{\tau+1}, I_\tau\}_{\tau=t}^{\infty}} E_t \sum_{\tau=t} \left(\frac{1}{1+r}\right)^{\tau-t} [\Pi(A_\tau, K_\tau) - I_\tau - G(I_\tau, K_\tau) \\ & -H(X_\tau, K_\tau) + q_\tau(I_\tau + (1-\delta)K_\tau - K_{\tau+1})], \end{aligned} \tag{OA 1.2}$$

where q_t is the shadow price of capital. The first-order conditions with respect to I_t and K_{t+1} are, respectively,

$$\frac{\partial \mathcal{L}}{\partial I_t} = 0 \Rightarrow q_t = 1 + \frac{\partial G(I_t, K_t)}{\partial I_t} + \frac{\partial H(X_t, K_t)}{\partial I_t}, \tag{OA 1.3}$$

$$\begin{aligned} & \frac{\partial \mathcal{L}}{\partial K_{t+1}} = 0 \Rightarrow \\ & q_t = \frac{1}{1+r} E_t \left[(1-\delta)q_{t+1} + \frac{\partial \Pi(A_{t+1}, K_{t+1})}{\partial K_{t+1}} - \frac{\partial G(I_{t+1}, K_{t+1})}{\partial K_{t+1}} - \frac{\partial H(X_{t+1}, K_{t+1})}{\partial K_{t+1}}\right]. \end{aligned} \tag{OA 1.4}$$

With the iterative substitution of (OA 1.4) and the transversality condition which requires that $\lim_{T\to\infty} q_{t+T}/(1+r)^{t+T} = 0$, we obtain

$$q_t = E_t \sum_{\tau=t+1}^{\infty} \frac{(1-\delta)^{\tau-t-1}}{(1+r)^{\tau-t}} \left(\frac{\partial \Pi(A_\tau, K_\tau)}{\partial K_\tau} - \frac{\partial G(I_\tau, K_\tau)}{\partial K_\tau} - \frac{\partial H(X_\tau, K_\tau)}{\partial K_\tau} \right). \tag{OA 1.5}$$

The substitution of (OA 1.3) into (OA 1.4) yields

$$\begin{aligned} & 1 + \frac{\partial G(I_t, K_t)}{\partial I_t} + \frac{\partial H(X_t, K_t)}{\partial I_t} = \\ & \frac{1}{1+r} E_t \Bigg[(1-\delta) \Bigg(1 + \frac{\partial G(I_{t+1}, K_{t+1})}{\partial I_{t+1}} + \\ & \frac{\partial H(X_{t+1}, K_{t+1})}{\partial I_{t+1}} \Bigg) + \frac{\partial \Pi(A_{t+1}, K_{t+1})}{\partial K_{t+1}} - \frac{\partial G(I_{t+1}, K_{t+1})}{\partial K_{t+1}} - \frac{\partial H(X_{t+1}, K_{t+1})}{\partial K_{t+1}} \Bigg]. \end{aligned} \tag{OA 1.6}$$

When constructing the empirical equation, we assume that the production function displays constant returns to scale in a perfectly competitive output market so that $\partial \Pi(A_t, K_t)/\partial K_t = \Pi_t/K_t$. Assuming further the quadratic adjustment cost function, we obtain $\partial G(I_t, K_t)/\partial I_t = \gamma I_t/K_t$ and $\partial G(I_t, K_t)/\partial K_t = -0.5\gamma \left(I_t/K_t\right)^2$. Also $\partial H(X_t, K_t)/\partial I_t = b\phi(I_t/K_t - \Pi_t/K_t)$ and $\partial H(X_t, K_t)/\partial K_t = -0.5 b\phi \left(I_t K_t - \Pi_t/K_t\right)\left(I_t K_t + \Pi_t/K_t\right)$. Adding an expectation error ϵ_{t+1} where $E_t(\epsilon_{t+1}) = 0$ to remove the expectation operator, we arrive at the empirical counterpart of the Euler equation:

$$\begin{aligned} & \frac{1}{1+r} \Bigg[(1-\delta) \left(1 + \gamma \left(\frac{I_{t+1}}{K_{t+1}} \right) + b\phi \left(\frac{I_{t+1}}{K_{t+1}} - \frac{\Pi_{t+1}}{K_{t+1}} \right) \right) + \\ & \frac{\Pi_{t+1}}{K_{t+1}} + \frac{1}{2}\gamma \left(\frac{I_{t+1}}{K_{t+1}} \right)^2 + \frac{1}{2} b\phi \left(\frac{I_{t+1}}{K_{t+1}} - \frac{\Pi_{t+1}}{K_{t+1}} \right) \left(\frac{I_{t+1}}{K_{t+1}} + \frac{\Pi_{t+1}}{K_{t+1}} \right) \Bigg] + \epsilon_{t+1} \\ & = 1 + \gamma \left(\frac{I_t}{K_t} \right) + b\phi \left(\frac{I_t}{K_t} - \frac{\Pi_t}{K_t} \right). \end{aligned} \tag{OA 1.7}$$

OA 2 Evidence based on industry-level data

Following the strand of literature that relates adjustment costs to the productivity growth, we adopt the approach of Bessen (2002) and estimate the trend of adjustment costs with 4-digit SIC code industry-level data from NBER-CES Manufacturing Industry Database for period 1977-2011. The adjustment cost is defined as the deviation of the actual output from potential output. For each industry j, the actual output is $Y_t = Y_t^*(1 - G_t)$, with potential output being equal to $Y_t^* = A_t K_t^{\alpha_{K,t}} M_t^{\alpha_{M,t}} L_t^{\alpha_{L,t}}$. Here, A_t denotes productivity shock, M_t (L_t) is material (labor) input, $\alpha_{K,t}$ ($\alpha_{M,t}$, $\alpha_{L,t}$) is the elasticity of output with respect to capital (material, labor). $G_t = \gamma I_{t-1}/K_{t-1}$ is the adjustment cost per unit of potential output, which is linearly related to the lagged investment-to-capital ratio. $1 - G_t$ is analogous to the speed of adjustment (SOA), as in the partial adjustment model of Lintner (1956). For the industry j at time t, we transform levels into logarithms, take the differences and rearrange $Y_{jt} = Y_{jt}^*(1 - G_{jt})$ to obtain ($\widehat{\cdot}$ denotes a log change):

$$\widehat{Z_{jt}} \equiv \widehat{Y_{jt}} - \alpha_{K,jt}\widehat{K_{jt}} - \alpha_{M,jt}\widehat{M_{jt}} - \alpha_{L,jt}\widehat{L_{jt}} = \widehat{A_{jt}} - \gamma\Delta\frac{I_{jt-1}}{K_{jt-1}}. \tag{OA 2.1}$$

Parameter γ can be estimated by regressing $\widehat{Z_{jt}}$ on the lagged change of investment-to-capital ratio, $\Delta(I_{j,t-1}/K_{j,t-1})$. In order to infer the time-series pattern of adjustment costs, we include the period trend variable T which equals 1 for 1977-1981, 2 for 1982-1987 and so on. Table OA1 presents the regression output for the pattern of adjustment costs. The coefficient of $T \times \Delta(I_{j,t-1}/K_{j,t-1})$ shows that the adjustment cost parameter increases by 0.053 (0.052 with industry fixed effects) in each period when time fixed effects are not included and by

TABLE OA1
Adjustment to the potential output level

Regression output based on data from NBER-CES Manufacturing Industry Database covering periods between 1977 and 2011. The dependent variable is productivity residual growth $\widehat{Z_{jt}}$ as described in Bessen (2002). The explanatory variables are lagged change of investment-to-capital ratio $\Delta\frac{I_{j,t-1}}{K_{j,t-1}}$, interaction term between period trend variable T, lagged change of investment-capital ratio and, depending on specification, industry and year fixed effects (FE). Period trend variable is defined as 1 in 1977-1981 and 2 in 1982-1986 and so forth. Standard errors are clustered in industry level and reported in the parentheses. Adjusted R^2 (R_a^2) is also reported. The number of observations is 15,953. ***, **, and * indicate significance at the 1%, 5%, and 10% level, respectively.

Variables	Dependent variable is $\widehat{Z_{jt}}$		
$\Delta\frac{I_{j,t-1}}{K_{j,t-1}}$	-0.094	-0.099	-0.196^{**}
	(0.085)	(0.098)	(0.087)
$T \times \Delta\frac{I_{j,t-1}}{K_{j,t-1}}$	-0.053^{**}	-0.052^{***}	-0.015
	(0.019)	(0.021)	(0.019)
Industry FE	N	Y	Y
Year FE	N	N	Y
R_a^2	0.015	0.014	0.127

0.015 (although not statistically significant at standard levels) once they are added. Even though the upward trend of adjustment costs is less pronounced when aggregate shocks are controlled for, the coefficient of $T \times \Delta(I_{j,t-1}/K_{j,t-1})$ has the expected sign, consistent with an increase in adjustment costs.

OA 3 Firm-level data cross-sectional evidence

To provide an additional set of tests, we exploit the cross-sectional variation in the level of knowledge capital stock as the foundation for capital adjustment costs. Specifically, we perform the analysis along the lines of Moshirian et al. (2017), who investigate differences in I-CF sensitivity patterns between developing and developed economies, as well as compare the trends of I-CF sensitivity between high-tech and non high-tech industries. To the extent that increasing capital adjustment costs can be a consequence of knowledge capital accumulation, we expect that countries that are more equipped to adopt the new technology (i.e., developed countries) or industries that rely more on advanced technology (i.e., high-tech industries) exhibit a more pronouced rise in capital adjustment costs and thereby a stronger decline in I-CF sensitivity.

OA 3.1 Cross-country regression results

Moshirian et al. (2017) examine the difference in I-CF sensitivities between firms from developed economies and those from developing countries. They demonstrate that the decrease in I-CF sensitivity is quite substantial for the former group and only moderate for the latter. It is argued that the declining importance of the productivity of tangible assets combined with a reduction in income predicability leads to the decreasing pattern of I-CF sensitivity in the "new economy". We replicate the OLS analysis of Moshirian et al. (2017) and complement it with the GMM5 approach. As in Moshirian et al. (2017), we estimate the time-series trend of I-CF sensitivity for developed countries (excluding the U.S.) and emerging economies (excluding China and India).[1] The level of a country's economic development is defined according to the MSCI classification. We estimate coefficients of investment on cash flow over a rolling window of 5 years for both sets of economies. As q is more likely to be measured with error for this international sample, we apply an additional filter and remove the observations where its magnitude exceeds 100 or is below 0. We begin from year 1995 to ensure that there are at least 200 observations each year for each developing country.

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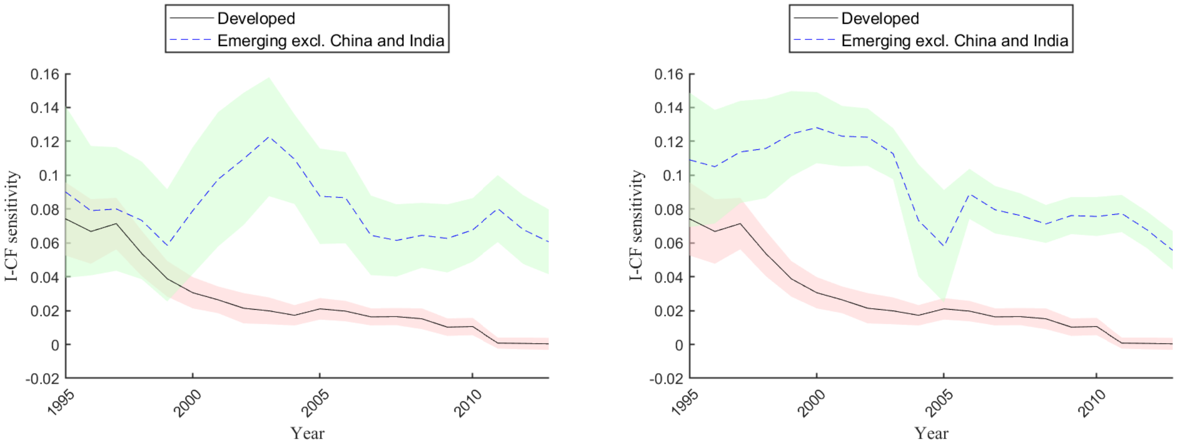
[1] The exclusion of China and India is motivated by Moshirian et al. (2017) as driven by their fast pace of adopting new technologies, which makes them less comparable with other developing countries.

FIGURE OA1
Investment-cash flow sensitivity of developed economies vs. developing countries


OLS

GMM5

I-CF sensitivity estimates based on the ordinary least squares (OLS), and Erickson-Whited error-corrected estimator (GMM5). The solid black line shows the estimates for developed economies excluding the U.S. and the dashed blue line shows the estimates of I-CF sensitivity for emerging countries excluding China and India. Shaded areas represent confidence intervals at the 95% level.

We present the rolling-window estimated coefficients in Figure OA1.

The decline of I-CF sensitivity for developing countries is less steep than for developed economies. Based on the OLS analysis, we conclude that I-CF sensitivity is declining over time in advanced economies but remains flat and does not drop until the most recent periods in developing countries. The decreasing trend of I-CF sensitivity for developed economies and the absence of such a clear decline for less developed economies are still visible when the error-corrected estimator GMM5 is used (the right panel of Figure OA1). The estimated I-CF sensitivity in developed economies starts from 0.07 in 1995-2000 and drops to near zero in 2010-2018 for GMM5 estimator. The estimate of I-CF sensitivity for the GMM5 estimator in less developed economies fluctuates around 0.10 until almost 2003 before it experiences a slight reduction.

We provide an alternative to Moshirian et al.'s (2017) explanation for the observed difference in I-CF sensitivities between developed economies and developing economies based on the implications of capital adjustment costs. Firms in developed countries are faster in adopting knowledge capital and hence should experience a more rapid increase in their capital adjustment costs year on year. Therefore, their I-CF sensitivities decline substantially, also when the productivity of physical capital, as proxied by q, is fully controlled for and the measurement error in q is corrected for. Firms in the developing economies, however, face a more moderate pace of technological change and, hence, a slower increase in their capital adjustment costs. Therefore, their I-CF sensitivities decline at a lower pace or face no decline at all, at least until recently.

OA 3.2 Cross-industry regression results

In the second part of the cross-sectional analysis, we classify manufacturing firms into belonging to either non-high-tech or high-tech industries. According to Chen and Chen's (2012), high-tech firms are those with SIC codes 3840-3849, 3820-3829, 3670-3679, 3660-3669, 3570-3579, and 2830-2839. Within each industry group, we run the baseline regression (1) for 9 periods from 1977-1981 to 2017-2019. As high-tech firms are likely to accumulate knowledge capital more quickly compared to non high-tech groups, we expect that the former experience a more rapid increase in capital adjustment costs over time and, therefore, a steeper decline in I-CF sensitivity.

Table OA2 shows a decreasing pattern of I-CF sensitivity regardless of the industry group the firms belong to. It also demonstrates that I-CF sensitivity for the high-tech industries

TABLE OA2
Estimation across industry groups

Estimation results for the baseline I-CF regression for two industry groups. Columns 2 and 4 (3 and 5) report coefficients β_1 of q (β_2 of cash flow) for two industry groups: high-tech and non high-tech, respectively. The p value for the null hypothesis that the coefficients are the same between the first period and the last period is reported below. ***, **, and * indicate significance at the 1%, 5%, and 10% level, respectively.

	High-tech:		Non high-tech:	
Period	β_1	β_2	β_1	β_2
1977-1981	0.032^{***}	0.276^{***}	0.015^{***}	0.268^{***}
1982-1986	0.022^{***}	0.113^{***}	0.021^{***}	0.144^{***}
1987-1991	0.017^{***}	0.054^{***}	0.013^{***}	0.062^{***}
1992-1996	0.011^{***}	0.044^{***}	0.010^{***}	0.049^{***}
1997-2001	0.006^{***}	0.013^{*}	0.011^{***}	0.036^{***}
2002-2006	0.006^{***}	-0.001	0.007^{***}	0.017^{*}
2007-2011	0.006^{***}	-0.002	0.008^{***}	0.001
2012-2016	0.004^{***}	-0.006	0.004^{***}	0.009
2017-2019	0.002^{***}	-0.007	0.005	0.010
p value	0.000	0.000	0.000	0.000

has declined in 2000s more rapidly than for other industries. For the former group, I-CF sensitivity starts to disappear and becomes statistically not significant in 2002-2006. It also remains lower in the most recent sample periods compared to the non high-tech group. In order to quantify the magnitude of the difference in the decline of I-CF sensitivity between high-tech and non high-tech industries, we estimate β_2 by year and regress it on the natural logarithm of the year trend variable T, which is equal to 1 for 1977, 2 for 1978 and so on. Table OA3 shows that I-CF sensitivity drops by on average 8.6% every year for the high-tech group whereas it decreases by only 7% for the non high-tech group. The reported t-statistics and the corresponding p-values for the null hypothesis that the declining trend of β_2 is the same for high-tech and non high-tech groups indicate that the declining trend of β_2 is significantly more prominent for the high-tech firms than that for their non high-tech counterparts.

TABLE OA3
Comparison of the trend in β_2 across industry groups

Estimates of the declining trend for β_2 across both industry groups, i.e., high-tech and non high-tech. The model is estimated by regressing β_2 on the natural log of year trend variable T, which is equal to 1 for 1977, 2 for 1978 and so on. Standard errors are shown in parentheses. t-statistics and corresponding p-values for the null hypothesis that the declining trend is the same between high-tech and non high-tech sectors are reported. ***, **, and * indicate significance at the 1%, 5%, and 10% level, respectively.

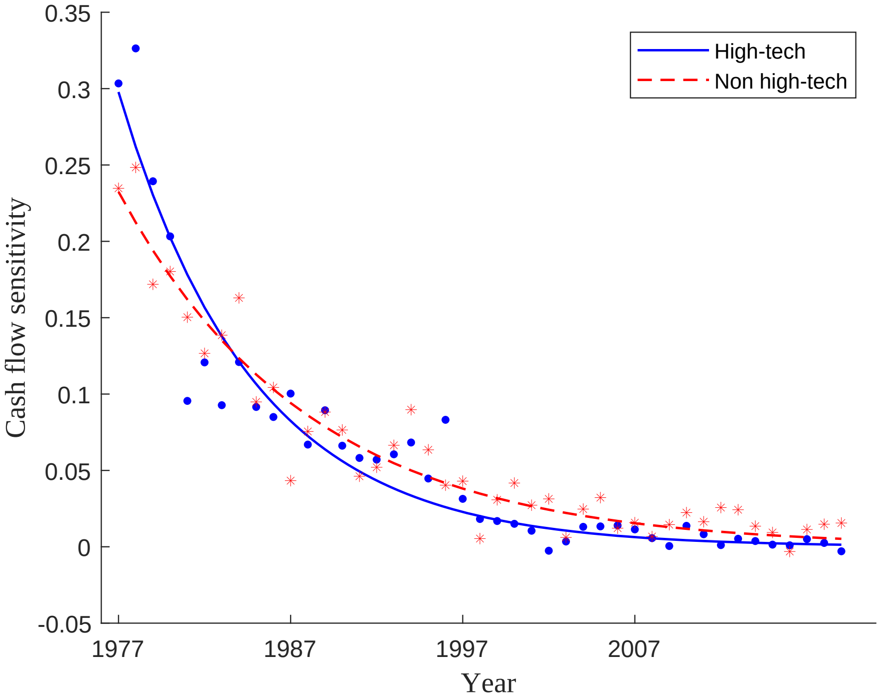
	β_2 high-tech	β_2 non high-tech	
$\log(T)$	-0.086^{***}	-0.070^{***}	
	(0.004)	(0.003)	
H0: Coeff. high-tech = coeff. non high-tech			
t-stat.:	-3.005	p-value:	0.000

The comparison of the declining trends is further illustrated in Figure OA2 with scatter plots and exponential curve fitting. It shows that high-tech firms have experienced a more substantial decline in their I-CF sensitivities, which is consistent with the view that they are more affected by the increasing costs of capital adjustment due to their higher pace of knowledge capital accumulation.

FIGURE OA2

Investment-cash flow sensitivity across groups by year (fitted with an exponential curve)

High-tech vs. non high-tech



Scatter plots of investment-cash flow sensitivities estimated for firms in high-tech (solid blue) vs. non high-tech (dashed red) industries fitted with an exponential curve.

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