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

Shushu Liao[†], Ingmar Nolte[‡], Grzegorz Pawlina[§]

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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. The result is corroborated in the supplementary analysis that exploits the cross-country and cross-industry variation of capital adjustment costs, as proxied by the level of technological advancement. 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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[†] `shushu.liao@aut.ac.nz`, Department of Finance, Auckland University of Technology, Auckland, New Zealand.

[‡] `i.nolte@lancaster.ac.uk`, Department of Accounting and Finance, Lancaster University Management School, Lancaster, LA1 4YX, UK.

[§] Corresponding author: `g.pawlina@lancaster.ac.uk`, Department of Accounting and Finance, Lancaster University Management School, Lancaster, LA1 4YX, UK.

1 Introduction

One of the key research areas in corporate finance studies 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) is 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). However, 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). In particular, Erickson and Whited (2000, 2002) point out that the observed empirical I-CF sensitivity can be spurious as Tobin's average 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).[1] 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). Consistent with the information role of cash flow, Chen, Goldstein and Jiang (2007) show that investment-q (I-q) sensitivity is higher and thereby I-CF sensitivity is lower

[1]The (observable) Tobin's average q is equal to the marginal q if and only if the production function displays constant returns to scale in a competitive market and the adjustment cost function is linearly homogeneous to investment and capital (Hayashi, 1982).

when the stock price is more informative.[2] Therefore, I-CF sensitivity can be an outcome of low stock price informativeness or the poor quality of an empirical proxy for marginal q.

The above contributions, however, base their conclusions on the cross-sectional comparison of I-CF sensitivity. Relatively few papers exploit its time-series pattern. Allayannis and Mozumdar (2004) are the first to conclude declining I-CF sensitivity between periods 1977-1986 and 1987-1996. Their paper spurred an active 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 (2020) 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.[3]

In this paper, 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. Most previous studies examine how the financial situation of a firm affects its investment policy by adding cash flow to the regression and comparing I-CF sensitivity across groups of firms sorted according to the characteristics that are assumed to capture the degree of

[2] Similarly, Bakke and Whited (2010) employ the errors-in-variables model in Erickson and Whited (2000, 2002) and model measurement error as part of Tobin's q that is unimportant for investment. They find that private information from the stock market reflects investment opportunities and affects investment.

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

financial constraints. In our framework, rather than relying on a priori measures of financial constraints based on (endogenous) firm-level variables, we directly incorporate external financing costs into a dynamic investment model, which allows us to generate predictions about the effects of both financing frictions and capital adjustment costs. To this end, we estimate the magnitude of the capital adjustment cost parameter 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.

Our results are 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. (We measure the degree of financial constraints by estimating the parameter that captures the cost of accessing outside finance and find no evidence of the decreasing cost.) We demonstrate that the 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.[4] 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 in the adjustment costs would result in a declining I-CF sensitivity. Our results support the hypothesis that it is the gradual increase of the adjustment cost parameter over time that significantly contributes to the observed declining I-CF sensitivity pattern.

[4]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.[5] It is further supported by the evidence from the extant literature as well as our own estimation results based on the first-order condition and the simulated method of moments (SMM) beginning with the firm's dynamic optimization problem. The evidence of the rising trend of adjustment costs remains robust to using alternative measures of Tobin's q as well as to the estimation performed on the basis of the Euler investment equation, which circumvents the use of a proxy for q. The SMM analysis, where model parameters of interest are selected to match the actual moments with simulated ones, yields results that support our earlier findings.

We argue that, based on the extant literature and available data on spending on high-tech equipment, increasing capital adjustment costs can be associated with the adoption of new technologies, e.g., the widespread use of computers and software, network and automated systems. 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). The adoption of high-tech equipment and machinery relies on specialist skills for the installation and subsequent operation and often results in costly retraining.[6] The relationship between I-CF sensitivity and adjustment costs is further corroborated in the supplementary analysis that exploits the cross-country and cross-industry variation of the capital adjustment costs, as proxied by the

[5]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. We provide analytical expressions for both I-CF and I-q sensitivities in Section 3.

[6]According to Clegg (2018), the online education program funded by AT&T to retrain the workforce "requires at least 10 hours' homework a week and take 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.

level of technological advancement.[7]

The paper contributes to the literature on corporate investment and financing decisions in several ways. Most significantly, we demonstrate that I-CF sensitivity can capture both financial frictions as well as capital adjustment costs. Investment is reliant on cash flow when it is costly to access the external financing market but it is *less sensitive* to cash flow in the presence of a higher capital adjustment cost. Empirically, we show 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 economic activities in explaining the responsiveness of investment to internal funds as in contrast with the frictions generated by financial markets.

To capture the evolution of the I-CF sensitivity, the paper uses time-varying model parameters. In this way, we are able to infer the time-series trend of economic parameters (most importantly, the capital adjustment cost). Furthermore, we address the problem of measurement error in q by applying alternative measures of q, re-estimating the relevant parameters based on the investment Euler equation, which does not require using q, and with the SMM methodology. Taken together, we provide robust evidence that the capital adjustment cost parameter is increasing over time.[8]

The remainder of the paper is structured as follows. Section 2 describes data sources as well as variables used and documents the decreasing pattern of I-CF sensitivity. In Section 3, we develop testable hypotheses for the predicted sign of the changes in I-CF sensitivity as a result of changing key parameters of the q model of investment. Section 4 presents the estimation results for key model parameters and offers a discussion of the way they can explain the declining pattern of I-CF sensitivity. Section 5 contains the supplementary analysis, whereas Section 6 concludes.

[7]To the extent that technological advancement and the resulting trend in capital adjustment costs are associated with a shift towards intangible capital, our results can be reconciled with Wang and Zhang (2020).

[8]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).

2 Dataset and baseline results

2.1 Data sources, variables and summary statistics

The data contains all U.S. manufacturing firms (SIC between 2000 and 3999) in the Compustat industry annual file, covering the period between 1977 and 2019. (Inside parentheses, we provide the name of the relevant data item in the Compustat industry annual file.) Investment, I, is measured as capital expenditure (*capx*) for annual data from 1977-2019. Capital, K, is defined as net property, plant and equipment (*ppent*). Tobin's average q, Q, is the 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*). 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. 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 is income before extraordinary items (*ib*) plus depreciation and amortization (*dp*).

Data variables, namely investment, Tobin's q and cash flow, 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 drop the 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 to mitigate the effect of outliers by year. 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).

Table 1 provides summary statistics for the regression variables. We divide the sample into five-year subsample periods, except for the latest period for which only three years of data are available. The descriptive statistics are provided for each of the subsample period. The mean and median levels of investment-to-capital ratio are relatively stable over time, and fluctuate around 0.2 between 1977-1981 and 2017-2019. The mean level of cash flow-to-capital ratio has dropped substantially in recent decades, from 0.42 in 1977-1981 to -0.506 in 2017-2019, while the mean level of Tobin's q has risen from 1.30 to 15.11 between late 1970s and the most recent period. The median level of cash flow-to-capital ratio remains relatively stable, while the median level of Tobin's q has increased over time from 0.82 in 1977-1981 to 5.60 in 2017-2019. Both the 25th percentile and 75th percentile of Tobin's q are increasing over time too, which suggests that the increase of Tobin's q is not limited to the subsample of value firms or growth firms. There is a considerable cross-sectional variation in Tobin's q and cash flow-to-capital ratio in the recent periods as indicated by greater dispersion between the 25th percentile and 75th percentile and larger standard deviations. Serial correlation (see Section 3 for details) of investment-to-capital ratio indicates the smoothness of investment behavior and rises from around 0.45 in 1980s to 0.57 in the most recent period. The proxy for Tobin's q is also highly autocorrelated, which has implications for the use of lagged instrumental variable to correct for the measurement error in q (Almeida et al., 2010; Erickson and Whited, 2012).

TABLE 1
Summary statistics for regression variables

Mean, standard deviation, percentiles and first-order serial correlation for investment-to-capital ratio, cash flow-to-capital ratio and Tobin's q for each subsample period from 1977-1981 to 2017-2019. The sample contains all manufacturing firms (SIC code between 2000 and 3999) in the U.S. for which relevant data is available in Compustat. I/K is the firm's capital expenditure, scaled by beginning-of-year 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. 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).

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

2.2 Baseline regression results and time-series variation of I-CF sensitivity

The baseline OLS regression equation for investment is

$$\frac{I_{it}}{K_{it}} = \beta_0 + \beta_1 Q_{it} + \beta_2 \frac{CF_{it}}{K_{it}} + \eta_i + \vartheta_t + \varepsilon_{it} \quad (1)$$

where I_{it}/K_{it} is firm's physical investment scaled by beginning-of-year capital, CF_{it}/K_{it} is firm's cash flow deflated by beginning-of-year capital, Q_{it} is the beginning-of-year Tobin's q, which is a proxy for investment opportunities or capital productivity, η_i denotes the firm-specific fixed effect, ϑ_t is the year fixed effect, and ε_{it} is a normally distributed error term. $\beta_i, i \in \{0, 1, 2\}$ denotes the relevant regression coefficient. We use the OLS estimator as well as the Erickson and Whited (2000, 2002) higher-order moment-based generalized method of moments (GMM) estimator (EW estimator), which is designed to mitigate the consequences of the measurement error in Q_{it}. We employ the fifth-order moment-based GMM estimator (GMM5) and a within-transformation is applied to remove the individual fixed effect.

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. Afterwards, I-CF sensitivity decreases. For 2002-2006, it becomes not significantly different from zero and remains so for all subsequent periods. Consistent with Chen and Chen (2012), similar decreasing pattern is observed when the EW estimator is applied. The latter result indicates that the decreasing trend of I-CF sensitivity is unlikely to be driven by the improved proxy quality of Tobin's q for capital productivity or decreased information content of cash flow (Moshirian et al., 2017).

Ağca and Mozumdar (2008) argue that the declining trend of I-CF sensitivity can be explained by the decreasing financial constraints as indicated by the rising fund flows, the

TABLE 2
Baseline linear regression results

Estimation results for the linear regression model employing both OLS and GMM5 (Erickson and Whited, 2000, 2002) estimators in each subsample period. The dependent variable is investment measured as the firm's capital expenditure, scaled by beginning-of-year net property, plant and equipment, The independent variables are cash flow, which is defined as income before extraordinary items plus depreciation, deflated by beginning-of-year net property, plant and equipment, and beginning-of-year Tobin'q, which is defined as the market value of capital over book value of capital (measured by net property, plant and equipment). β_1 (β_2) denotes the coefficient of q (cash flow). Robust standard errors are clustered at firm level and reported in the parentheses. The number of observations per period is also reported. The sample contains all U.S. manufacturing firms in Compustat over the 1977-2019 period. ***, **, and * indicate significance at the 1%, 5%, and 10% level, respectively.

Period	OLS		GMM5		
	β_1	β_2	β_1	β_2	Obs.
1977-1981	0.021***	0.271***	0.101***	0.207***	7994
	(0.004)	(0.021)	(0.009)	(0.020)	
1982-1986	0.022***	0.131***	0.060***	0.069***	8033
	(0.003)	(0.015)	(0.006)	(0.016)	
1987-1991	0.016***	0.058***	0.037***	0.046***	7714
	(0.002)	(0.009)	(0.003)	(0.009)	
1992-1996	0.010***	0.046***	0.026***	0.022***	8357
	(0.001)	(0.008)	(0.002)	(0.008)	
1997-2001	0.007***	0.022***	0.016***	0.022***	8680
	(0.001)	(0.006)	(0.002)	(0.006)	
2002-2006	0.006***	0.005	0.012***	0.002	7497
	(0.001)	(0.005)	(0.001)	(0.005)	
2007-2011	0.007***	0.000	0.010***	-0.002	6436
	(0.001)	(0.004)	(0.000)	(0.003)	
2012-2016	0.004***	-0.002	0.008***	-0.001	5451
	(0.001)	(0.004)	(0.001)	(0.004)	
2017-2019	0.003***	-0.004	-0.001	-0.009	2917
	(0.001)	(0.004)	(0.001)	(0.005)	

increasing number of analysts following, the number of firms with bond rating and the increasing proportion of large institutional ownership. By contrast, Chen and Chen (2012) show that I-CF sensitivity still decreases even for financially unconstrained firms and there is no indication of the relaxation of financing constraints as the volume of new external financing remains relatively stable.

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 additional cash flow. The presence of convex adjustment costs results in only a partial adjustment of capital towards its desired level and leads to a positive serial correlation of investment (see, e.g., Cooper et al., 1999; Caballero and Engel, 2003). Although Cooper and Haltiwanger (2006) report that the serial correlation of investment is low at the plant-level (estimated at 0.058), we show that the serial correlation is economically significant at the firm-level (see Table 1). To further motivate the choice of the convex adjustment costs (as opposed to fixed, or generally non-convex costs) in the modeling set-up, we allow the function of capital adjustment costs to take a more general form and test for its convexity in Section 4.

Capital adjustment cost is the expenditure incurred before the equipment or plant can be put to full use and it comprises installing costs (e.g., breaks in production during installation), 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. 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 the 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)).

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". From the perspective of sustainability, costs may occur to meet the high environmental standards when building existing plants or constructing new sites.

If firms had an unrestricted access to external finance, they would be able 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 is positive and does not only depend on the costs of obtaining outside financing but also on the costs of adjusting the capital level. Financially constrained firms increase their investment to a smaller extent upon receiving cash windfall when capital adjustment is costly. In this section, we formulate specific predictions on how external financing costs and adjustment costs affect I-CF sensitivity and provide evidence supporting the link between the trend of I-CF sensitivity and the intertemporal evolution of capital adjustment costs.

In the presented framework, time is discrete, I_t is investment at time t, K_t is capital stock that satisfies the standard intertemporal condition $K_{t+1} = I_t + (1-\delta)K_t$, with $\delta \geq 0$ denoting the depreciation rate. The adjustment cost, $G(I, K)$, depends on both investment and installed capital. The unit price of output and price of capital goods equal 1. To operationalize the notion of the adjustment cost, we set the adjustment cost function to $G(I, K) = \psi^{-1}\gamma(I/K)^{\psi}K$, where $\gamma > 0$ is a scaling factor and ψ reflects the elasticity of adjustment cost to investment rate. Parameter ψ equals 2 in a model where the adjustment cost is quadratic and the assumption of the quadratic cost is essential in deriving the linear baseline regression (cf. Lewellen and Lewellen, 2016). By allowing the adjustment cost function to take a more general form, we provide a test for the functional form of capital adjustment cost function, specifically whether the function is quadratic ($\psi = 2$).[9] $\Pi(A, K) = AK^{\alpha}$ denotes the profit function, where A is a stochastic profitability shock that determines the exogenous state of the firm and α is the curvature of the profit function (in Appendix A, we provide the derivation of the profit function). As in Gomes (2001) and Cooper and Ejarque (2003), we consider cash flow as a means to supply firms with internal funds to finance investment.

The way to model financial constraints is generally complex and we do not attempt to endogenize financial policy along the lines of Li, Whited and Wu (2016). As we are only interested in comparing the magnitude of financial frictions across periods, we model the cost of external financing as in Gomes (2001) and Cooper and Ejarque (2003). $H(X, K)$ is external financing cost function where X is the amount of external funds a firm needs to raise to meet its investment demand (cash flow shortfall). We assume that equity is the sole source of financing and is only issued when the firm is not able to fund the investment with its internal cash flow. Hennessy and Whited (2007) argue that cost of external equity decreases with firm size, hence the external financing cost is a function of capital K. In line with Krasker (1986), who finds that the shadow cost of equity increases with the number of shares issued, the external cost function is assumed to be convex and quadratic. We therefore impose the following form of the external financing cost function: $H(X, K) = 0.5b\Phi(X/K)^2K$. As in Cooper and Ejarque (2003) and Lewellen and Lewellen (2016), the amount of external financing X is defined as the gap between investment and cash flow. (Including the capital adjustment cost in X results in more complex calculations but does not substantially affect the main results.) Cash flow is the profit generated by the capital in place, and hence $X = I - \Pi$. Φ is an indicator which is equal to one if $I \geq \Pi$ and zero otherwise. Parameter b

[9]In Section 4, we empirically verify whether this assumption is plausible.

reflects the cost of external financing. Fazzari et al. (1988) characterize financial constraints as the wedge between the cost of internal capital and the cost of accessing external capital. A *ceteris paribus* higher cost of raising funds from the outside capital market (e.g., due to informational asymmetry, as in Myers and Majluf, 1984) is therefore equivalent to a higher magnitude of financing constraints.

Equityholders choose an investment policy to maximize the firm value taking into account the cost of external financing:

$$V(A_t, K_t) = \max_{I_t} [(\Pi(A_t, K_t) - I_t - G(I_t, K_t) - H(X_t, K_t)) + \theta E_{A_{t+1}|A_t} V(A_{t+1}, K_{t+1})], \quad (2)$$

where θ denotes the discount factor. The marginal Tobin's q (denoted subsequently by q_t) is defined as $\theta E_{A_{t+1}|A_t} V_K(A_{t+1}, K_{t+1})$, where $V_s(A, K)$ denotes the partial derivative of firm value V with respect to $s \in \{A, K\}$. The first order condition with respect to I, which equates the marginal return to the marginal cost of investment, yields the following equation for q:

$$1 + \gamma \left(\frac{I_t}{K_t} \right)^{\psi - 1} + b\Phi \left(\frac{I_t}{K_t} - \frac{\Pi_t}{K_t} \right) = q_t. \quad (3)$$

Based on eq. (3), the partial derivative of investment with respect to cash flow is obtained:

$$\frac{\partial I/K}{\partial \Pi/K} = \frac{b\Phi}{\gamma(\psi - 1)(\frac{I}{K})^{\psi-2} + b\Phi}. \quad (4)$$

Details of the derivation are outlined in Appendix B. Provided that $\gamma > 0$, a lower magnitude of b is associated with a more muted response of investment to incremental cash flow. As it is possible that the decreasing I-CF sensitivity is the result of declining financing cost parameter, we formulate the following empirical prediction:

H1: *Cash flow sensitivity of investment decreases as a result of lower costs of external financing.*

From (4), we obtain that γ is negatively related to the partial derivative of investment with respect to cash flow. (In Appendix C, we also derive the expression for the firm value considering a *fixed* capital adjustment cost based on Whited (2006) and demonstrate that such a form of that cost can also lead to a negative relationship between capital adjustment costs and I-CF sensitivity.) This result can be explained as follows. If the firm is financially constrained, its investment depends on the availability of internal funds. However, this dependence becomes weaker with a higher adjustment cost as the firm is not willing to increase capital upon receiving one unit of cash flow when making such capital adjustment is costly. Therefore, an alternative explanation for the decreasing I-CF sensitivity over time could be 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 from financial markets (financing constraints).

Similarly, we can also obtain the partial derivative of investment with respect to q:

$$\frac{\partial I/K}{\partial q} = \frac{1}{\gamma(\psi - 1)(\frac{I}{K})^{\psi-2} + b\Phi}. \tag{5}$$

One can see from (5) that the partial derivative of investment to q is negatively related to both capital adjustment costs and financial frictions. The investment demand will vary less with the growth opportunities reflected in q if the firm's investment behavior is constrained by frictions in either financial markets or real economic activities. With that observation in mind, we offer a preliminary test of our predictions by looking 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 that decreasing I-CF sensitivity is driven by the rising 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.

4 Main results

4.1 Empirical implementation of the q equation

4.1.1 Estimation results with Tobin's q

In the baseline I-CF regression equation, such as eq. (1), cash flow is added to the investment-q equation typically in an *ad hoc* way and, therefore, little can be said *a priori* about the expected magnitude of I-CF sensitivity. A recent notable exception is Lewellen and Lewellen (2016), who incorporate the cost of external financing to the neoclassical investment model with quadratic adjustment costs to obtain the I-CF sensitivity equation. While Abel and Eberly (2011) provide theoretical micro-foundations for the existence of I-CF sensitivity in the absence of financing constraints, they do so under strong assumptions of no capital adjustment costs and a sufficient time-series variation in the drift rate of productivity.

In our approach, we follow Lewellen and Lewellen (2016) but relax the standard assumption of the quadratic adjustment cost. In addition, instead of relying on the baseline linear regression, in which q and cash flow are regressors, we provide estimates of model parameters based on the q equation, which is directly based on the first-order condition. Consequently, we let q become the dependent variable (with investment and cash flow taking the role of regressors) so that the measurement error in q does not affect parameter estimates as long as it is independent of both explanatory variables.

We start by estimating the model parameters based on the q equation.[10] The corresponding empirical equivalent of (3) is

$$Q_{it} = 1 + \gamma \left(\frac{I_{it}}{K_{it}} \right)^{\psi - 1} + b\Phi \left(\frac{I_{it}}{K_{it}} - \frac{CF_{it}}{K_{it}} \right) + \eta_j + \vartheta_t + \varepsilon_{it}, \tag{6}$$

where η_j is dummy variable for each two-digit SIC industry level and ϑ_t represents the year fixed effect.[11] Other variables are as those described in Section 2.1. Estimated parameters are b, ψ and γ and they all expected to be positive in an economically relevant scenario. We select the set of parameters that produce the least sum of squared error $\sum \varepsilon_{it}^2$. We present the estimation results in Panel A of Table 3.

As discussed, the likely mismeasured q becomes the dependent variable in the current setting. As a result, we still expect to obtain consistent estimates of relevant parameters as

[10] Even though it is may be more accurate to infer relevant parameters by matching the moments from a dynamic structural model that endogenizes a firm's investment policy to the moments observed in the sample, it is helpful first to understand the intuition about how model parameters affect I-CF sensitivity by looking at the partial derivative of investment with regard to cash flow derived from the q equation. (In a more complex model of firm dynamics, such as Hennessy and Whited (2007), it is generally not possible to obtain a closed-form expression for the I-CF relationship.) We provide the parameters estimates based on the structural methods of moments in Section 4.3

[11] We use industry dummies instead of firm fixed effects due to the additional computational complexity associated with using the latter. Moreover, it may be more reasonable to aggregate short panel data at a higher level as regression may fail to capture the characteristics of firms who have single observation during the five-year subsample period if one uses firm-specific fixed effect. (Similarly, Lewellen and Lewellen (2016) are reluctant to include firm fixed effects to avoid imposing survivorship requirements and/or bias slope estimates if the number of observations per firm is low.) We find that between 10%-17% of the firms have single observation and around 30% of the firms have only two-year observations in the subsample period.

long as the measurement error is independent of the explanatory variables.[12] Therefore, the estimates of the parameters based on the q equation that has q as the regressand fare better than the ones implied from the reciprocal of β_1 and the ratio of β_2 and β_1 from regression (1). The adjusted R^2 shown in Column 5 of Panel A, Table 3 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 the elasticity parameter ψ are reported in Column 3 of Panel A, Table 3. They are all significantly larger than zero (and one, which supports the choice of the convex form of the capital adjustment cost function). Column 6 in Panel A, Table 3 presents the t statistics under the null hypothesis that $\psi = 2$. Most of the estimates of ψ are not significantly different from 2 at the 1% significance level, which yields support for the commonly used quadratic cost assumption. Even though Cooper and Haltiwanger (2006) argue that non-convex adjustment costs are more prominent for the *plant-level* data, we show that investment behavior at the *firm level* is consistent with convex (and quadratic) adjustment costs. Hence, from now on, we adopt a quadratic function for capital adjustment costs.

The parameter b, which measures the cost of external financing, reflects the degree of financial constraints. The relevant estimates are reported in Column 4, Panel A, Table 3. The estimate of b is significantly positive in most of the periods (it is not significantly different from zero only in 1977-1981).[13] The estimated b is much higher in late 2000s than in the earlier sample periods. If one interprets I-CF sensitivity as a measure of financial constraints,

[12]In Erickson and Whited (2000), measurement error is assumed to be independent of I/K and CF/K. Error that causes the deviation between marginal q and average q such as market power and interest rate might be considered as exogenous. Even if the measurement error in not independent, the biases induced by the measurement error in the explained variable can be translated into omitted variable biases. The factor variables that cause empirical average q to deviate from marginal q is regarded as omitted variables. Therefore, one can deal with the measurement error by incorporating into the estimation equation the factor variables that could possibly cause such difference between empirical average q and marginal q. We find that the parameter estimates including factor variables remain largely unchanged.

[13]Since we do not include cash savings into the funding gap, b measures the combined cost of using external equity funds and spending out of cash, with the latter being effectively zero.

one would expect 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 have *not* become more relaxed in recent years. Also, studies such as Almeida, Campello and Weisbach (2004) and Faulkender and Wang (2006) argue that constrained firms are more inclined to hold cash, with Bates, Kahle and Stulz (2009) showing that there is an increase in cash holding 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 the adjustment cost parameter γ, which is reported in Column 2 of Panel A, Table 3, fluctuates around 5 in early sample periods, increases to mid-teens in the 1990s and to above 25 in the 2000s. The positive trend of the adjustment cost parameter is therefore consistent with I-CF sensitivity declining over time. Investment responds less strongly to cash flow in late periods because capital adjustment is more costly. With respect to the magnitude of γ, previous studies, which typically 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.[14] For example, Gilchrist and Himmelberg (1995) obtain a γ as high as 20 during 1985-1989, which is similar to Hayashi (1982), who uses data from 1952-1978. The adjustment cost parameter estimated in our setting looks therefore more realistic, with parameter γ in the comparable period 1977-1991 being closer to 5, which is lower by the factor of 4. As stock-market-based Tobin's average q is considered as less reliable in measuring the investment opportunities (e.g., Cummins, Hassett and Oliner, 2006, among others), we provide further empirical evidence of the trend and the magnitude of capital adjustment costs in the following sections.

[14] For the quadratic adjustment cost function, an additional \$1 of investment leads to an incremental capital adjustment cost of $\$\gamma I/K$.

4.1.2 Estimation results with alternative measures of q

Average q (market-to-book capital ratio) is not a reliable proxy for marginal q if any of the linear homogeneity assumptions in Hayashi (1982) does not hold. To address the concern that the estimated upward trend of adjustment costs is driven by the imperfect proxy for marginal q, we rerun the estimation with alternative measures of q. Gala (2014) proposes a state-space measure of marginal q using capital stock and profitability shock.[15] The magnitude of the profitability shock can be inferred from the 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, following Gala (2014), 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 for Q (labelled as $\hat{Q}$) 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 $q = \widehat{Q}(1 + \widehat{a_2} + 2\widehat{a_4}\log(K) + \widehat{a_5}\log(A))$.

In the standard investment theory, marginal q is based on managers' evaluation of firm's fundamentals and any deviations of market valuations from managers' assessed fundamentals are regarded as "misvaluation" (Blanchard, Rhee and Summers, 1993). To alleviate the concern that the parameter estimates are confounded by the misvaluation component, we follow Goyal and Yamada (2001) and Campello and Graham (2013) as an alternative approach to estimating marginal q and use their fundamental q as another proxy for the firm's investment opportunities. 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.

[15] Similar to this approach, Gala et al. (2019) express investment policy as a function of state variables.

TABLE 3

Estimation results based on the q equation

Estimation results in Panel A is based on eq. (6) in each five-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 adjustment cost parameter, ψ measures the elasticity of adjustment cost ($\psi = 2$ 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. Q_{it} is defined as Gala's marginal q and fundamental q, respectively. Adjusted R^2 (R_a^2) in both Panel A and Panel B is one minus mean squared error divided by the variance of Q_{it}. 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's marginal q:				Fundamental q:			
Period	γ	ψ	b	R_a^2	$t(\psi = 2)$	Period	γ	b	R_a^2	Period	γ	b	R_a^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)	

We repeat the nonlinear estimation of regression (6) with Gala's marginal q and the fundamental q as proxies for the (marginal) Tobin's q. (In both cases, we use the quadratic adjustment cost function given that the previous estimates ψ do not significantly differ from 2.) The results with Gala's q (reported on the left-hand side of Panel B, Table 3) show that the estimate of the adjustment cost parameter γ rises across periods from 0.029 in 1977-1981 to 4.213 in 2012-2016 and 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 is increasing over time and that the upward trend of the adjustment cost parameter is clearly present.

4.2 Empirical implementation of the Euler equation

As an alternative way of estimating capital adjustment costs, we use the investment Euler equation framework. The Euler equation, which equates the marginal cost of investment today with the expected discounted cost of waiting to invest tomorrow, has the advantage of avoiding the use of q and mitigating endogeneity concerns arising in the reduced-form regression approach (Kang et al., 2010). Using an intertemporal investment model and denoting the risk-free rate by r, one can express the maximization problem of a firm's shareholders as

$$V(A_t, K_t) = \max_{\{K_{\tau+1}, I_\tau\}_{\tau=t}^{\infty}} E_t \sum_{\tau=t} \left(\frac{1}{1+r} \right)^{\tau-t} \left[\Pi(A_\tau, K_\tau) - I_\tau - G(I_\tau, K_\tau) - H(X_\tau, K_\tau) \right], \quad (7)$$

subject to

$$K_{t+1} = I_t + (1-\delta) K_t, \quad (8)$$

where the right-hand side of eq. (7) 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 $\Pi(\cdot)$.[16] By differentiating (7) with respect to K_{t+1} and adding an expectation error ϵ_{t+1}, where $E_t(\epsilon_{t+1}) = 0$ to remove the expectation operator, we arrive at the estimation equation for the Euler equation (details of the derivation are presented in Appendix D):

$$\begin{aligned}
&\frac{1}{1+r}\left[(1-\delta)\left(1+\gamma\left(\frac{I_{t+1}}{K_{t+1}}\right)+b\phi\left(\frac{I_{t+1}}{K_{t+1}}-\frac{\Pi_{t+1}}{K_{t+1}}\right)\right)+\right.\\
&\left.\frac{\Pi_{t+1}}{K_{t+1}}+\frac{1}{2}\gamma\left(\frac{I_{t+1}}{K_{t+1}}\right)^2+\frac{b}{2}\phi\left(\frac{I_{t+1}}{K_{t+1}}-\frac{\Pi_{t+1}}{K_{t+1}}\right)\left(\frac{I_{t+1}}{K_{t+1}}+\frac{\Pi_{t+1}}{K_{t+1}}\right)\right]+\epsilon_{t+1}\\
&=1+\gamma\left(\frac{I_t}{K_t}\right)+b\phi\left(\frac{I_t}{K_t}-\frac{\Pi_t}{K_t}\right).
\end{aligned} \tag{9}$$

We follow Whited (1998) and employ the two-step GMM to estimate the parameters in (9). Any information set at time t is orthogonal to the expectation error at time $t+1$. Therefore, we use GMM to estimate the parameters with the moment condition $E(Z_t\epsilon_{t+1}) = 0$, where Z_t denotes a set of instruments. The instrument set consists of 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. The estimation results are provided in Table 4. The results of the test for overidentifying restrictions (J test) indicate that the overidentifying restrictions are rejected in most of the early periods. 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 is better in the later periods. In Column 2 of Table 4, it can be seen that the adjustment cost parameter estimates oscillate around zero in the early periods and start exceeding 8 in 2010s. The estimation results based on the Euler equation unequivocally support hypothesis H2 that it is an upward trend in capital adjustment costs that results in

[16]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. (7). The instrument sets consist of time dummy variables, lagged value of investment-capital ratio, cash flow-capital ratio, debt-capital ratio, current asset-capital ratio, capital spending, sales growth and cash reserve. 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-value (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	8.206***	0.000	10.635
	(1.595)	(0.019)	(0.560)

the decreasing pattern of I-CF sensitivity.

4.3 Evidence based on structural estimation of parameters

4.3.1 Constant adjustment cost parameter

To complement the analysis of Sections 3 and 4.1-4.2, we estimate relevant model parameters using the SMM approach. SMM does not require a proxy for q but also avoids the need to choose instruments, as in the estimation of the Euler equation. We perform the simulation study based on the investment-q model. The functional form of the profit, adjustment costs and financing costs are the same as in Section 3. We are interested in identifying parameter values of the model that would result in matching relevant properties of the actual data, which in this case are the coefficients of the baseline regression (1). The key parameters of interest are the capital adjustment cost (γ) and the magnitude of financing constraints (b). For simplicity, we first assume that firms are myopic and γ is perceived as constant within each five-year period. For each period, we estimate the relevant model parameters, γ and b, by matching the actual moments with the moments generated from the simulated data. The moments we aim to match are the q sensitivity of investment, β_1, and cash flow sensitivity of investment, β_2.

Our estimation framework is as follows. 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:

$$a' = \rho_a a + \epsilon', \tag{10}$$

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

$$\begin{aligned} p(j,i) &= \Pr[\bar{a}_i - w/2 \leq \rho_a \bar{a}_j + \epsilon' \leq \bar{a}_i + w/2] \\ &= N\left(\frac{\bar{a}_i - \rho_a \bar{a}_j + w/2}{\sigma_a}\right) - N\left(\frac{\bar{a}_i - \rho_a \bar{a}_j - w/2}{\sigma_a}\right). \end{aligned} \tag{11}$$

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 equal to 0.45. We set autoregressive coefficient ρ_a to 0.65, whereas σ_a is 0.15. Finally, the depreciation rate δ is set to 0.15 and risk-free rate r to 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:

$$\hat{\Theta} = \arg\min_{\Theta} \left[M_d - \frac{1}{S} \sum_{s=1}^{S} m_s(\Theta) \right] W \left[M_d - \frac{1}{S} \sum_{s=1}^{S} m_s(\Theta) \right], \tag{12}$$

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 our simulated moments.

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

The estimation output for each subsample period is reported in Table 5. 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.

4.3.2 Time-varying adjustment cost parameter

To relax the assumption of the firms' myopia, we reexamine the value-maximization problem with a time-varying adjustment cost parameter. In this set-up, firms are fully rational and correctly update the distribution of the adjustment cost parameter in the next period based on its current level. We allow γ to vary according to a finite-state Markov-chain process. This results in three state variables for a firm's optimization problem: profitability shock A, capital stock K and the adjustment cost parameter γ. We rewrite the firm's value as

$$V(A, K, \gamma) = \max_I [(\Pi(A, K) - I - G(I, K, \gamma) - H(X, K)) + \theta E_{\{A'|A;\gamma'|\gamma\}} V(A', K', \gamma')], \quad (13)$$

where the logarithm of γ follows an AR(1) process:

$$\log(\gamma^{'}) = \mu_g + \rho_g \log(\gamma) + \sigma_g \epsilon_g^{'}, \tag{14}$$

with $\epsilon_g \sim N(0,1)$ representing the aggregate shock to investment frictions. The mean reverting property of the process ensures the (long-run) stationarity of capital adjustment costs. The difference $1 - \rho_g$ captures the speed of mean reversion and it holds that $0 < \rho_g < 1$ to ensure that capital adjustment cost does not explode. The volatility of the adjustment cost process is denoted by σ_g. Parameter μ_g is a constant term, where $\mu_g/(1-\rho_g)$ defines the mean level that $\log(\gamma)$ tends to revert to. The initial level of γ (denoted as γ_0) matters as it determines the (initial) trend of the process. The mean level of γ equals $\exp\left(\mu_g/(1-\rho_g) + 0.5\sigma_g^2/(1-\rho_g^2)\right)$. If γ_0 is lower (higher) than the mean level, then γ initially tends to rise (fall) over time. The parameters that we estimate to match as closely as possible the empirical time-series pattern of investment-cash flow sensitivity are $[\gamma_0\ \rho_g\ \mu_g\ \sigma_g\ b\ \alpha\ \rho_a\ \sigma_a]$, where the subset $[\gamma_0\ \rho_g\ \mu_g\ \sigma_g]$ determines the dynamics of capital adjustment costs. For the parameter set chosen, we solve for the model and simulate one time-series of γ for all firms and one time-series of A for each of the firm. Our simulation consists of 10 panels, each of which includes 1000 firms and 80 periods. We start the simulation with randomly-drawn firm-specific profit shocks (A) and the corresponding no-adjustment-cost steady-state capital (K). We set γ to γ_0 for the first 20 periods and, subsequently, remove those observations to eliminate the effect of the initial condition. We match the simulated cash flow coefficients (β_2) estimated per period with those estimated yearly from the actual data. This procedure is equivalent to matching 40 moments, each corresponding to the cash flow coefficient in a single year.

The estimation is carried out to match the time-series variation of β_2. The parameter set that delivers the pattern closest to that in the actual data is outlined in Table 6. The left-hand side graph in Figure 1 plots the evolution of the simulated adjustment cost parameter.

TABLE 6
Parameter estimation results based on the SMM for time-varying γ

Parameters of capital adjustment costs:		
Mean reversion coefficient	ρ_g	0.931
Initial γ	γ_0	1.717
Mean of $\log(\gamma)$	μ_g	0.083
Volatility of $\log(\gamma)$	σ_g	0.040
The long-run mean	$e^{\frac{\mu_g}{(1-\rho_g)}+0.5\frac{\sigma_g^2}{(1-\rho_g^2)}}$	3.335
Other parameters:		
Financing cost	b	0.500
Returns to scale	α	0.701
Mean reversion coefficient of productivity	ρ_a	0.651
Volatility of productivity	σ_a	0.151

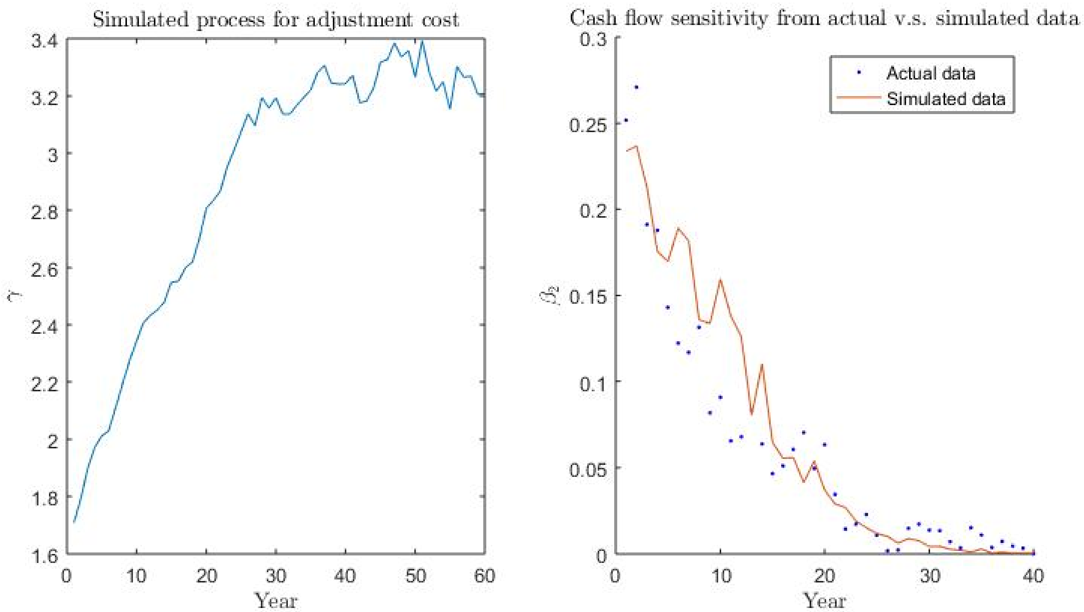
It starts from approximately 1.7 and increases up to 3.3. The corresponding investment-cash flow sensitivity regressed with the model-simulated data is plotted with solid line on the right-hand side graph. The deviations of simulated β_2 from actual β_2 are generally minor except for a few years at the beginning of the sample period. Again, an increasing trend of γ is observed (with the estimated γ_0 being lower that the long-run mean), which is consistent with the decreasing pattern of β_2.

4.4 Evidence based on the industry-level data

4.4.1 Technological change and capital adjustment costs

The innovation of technology has evolved significantly over the past 40 years. In 1977, Ken Olsen, co-founder of the Digital Equipment Corporation, is quoted saying "There is no reason for any individual to have a computer in his home" (Boaz and Crane, 1985), while rather the opposite has been true in more recent decades. According to Hindle (2012), technological breakthroughs can be disruptive as "they completely overturn existing products and markets". An industry report from PwC refers to 3D printing as a disruptive technology and lists the shortage of talent, the need to establish digital platforms and restructure the

FIGURE 1
Simulated process of γ and estimated β_2 (SMM)



Evolution of adjustment cost parameter simulated with the parameter set in Table 6 (left-hand side) and the corresponding investment-cash flow sensitivity based on a regression using model-simulated and actual data, depicted with the solid line and dots, respectively (right-hand side).

current operations as well as the demand for a new system to permit integration of activities as the associated costs of its adoption (PwC, 2016). 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 the associated cost of time for labor to retrain into the highly skilled positions.

Extant academic literature, which typically relies on the industry-level data, offers similar insights referring to the technological progress as a significant contributor to the increase of capital adjustment costs. Hornstein and Krusell (1996) as well as 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

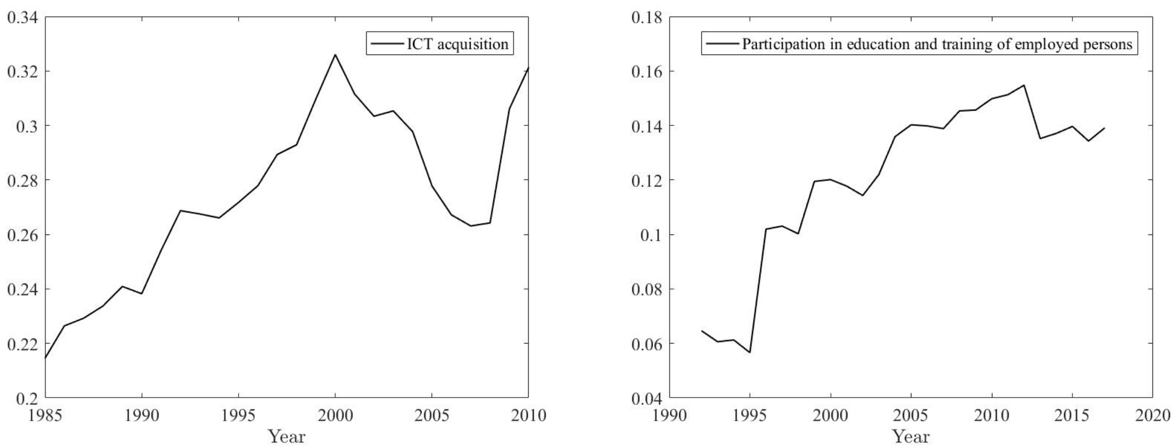
Bessen (2002) attributes increasing adjustment costs to an increase in spending on information technology, for instance, on customization of software. Groth (2008) estimates that it is particularly costly to install capital in ICT-intensive industries (see also Bessen (2002), who reports high adjustment 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.[17]

As documented in Gordon (1990), the rate of technology growth, as implied by the decline in the relative price of investment goods, has been significant (Oliner and Sichel, 2000; Jorgenson and Stiroh, 2000). Panel (a) of Figure 2 illustrates the increasing trend (with the exception of the aftermath of the dotcom bubble) in the acquisition of ICT equipment and software in the U.S. The adoption of new technology results in firms needing to provide adequate training to enable their workforce to achieve expected productivity gains associated with it. In the short-run, when workers devote extra hours to acquiring new skills and effectively forgo some output, capital adjustment costs arise. In Panel (b) of Figure 2, we present the evolution of the rate of participation in educational and training programs in European countries to demonstrate the broader trend prevailing in highly industrialized economies. Specifically, using Eurostat data, we plot the average of participation rate in education and training by employed persons across 17 Western European countries between 1992 and 2017 (the training participation rate has been reported since 1992). The percentage of employees taking part in eduction and training rises to approximately 14% in most recent years from around 6% in 1992. This observed increase in the participation rate in education and training programs are symptomatic of higher adjustment costs associated with the adoption of new technologies.

[17]One of the few examples of the opposite view is Meghir, Ryan and Van Reenen (1996), who argue that innovative firms face lower adjustment costs as innovation brings more flexibility (see also Smolny (1998)). However, their approach differs from ours as they primarily base their conclusions on the evidence from the labor market.

FIGURE 2
Acquisition of high-tech equipment and workers' participation in training

(a) ICT acquisition (b) Participation in education and training



Acquisition of equipment and computer software between 1985 and 2011 for the U.S. (panel (a)) and the average percentage of employed persons in 17 European countries that have taken part in education and training between 1992 and 2017 (panel (b)).

4.4.2 Estimation with 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 the potential output. For each industry j, we have $Y_t = Y_t^*(1-G_t)$ where the potential output is $Y_t^* = A_t K_t^{\alpha_{K,t}} M_t^{\alpha_{M,t}} L_t^{\alpha_{L,t}}$, where 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), and Y_t is the actual output. $G_t = \gamma I_{t-1}/K_{t-1}$ 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

TABLE 7
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 and lagged change of investment-capital ratio. 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 is also reported. ***, **, 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 dummies		Yes	Yes
Year dummies			Yes
R_a^2	0.015	0.014	0.127

and rearrange $Y_{jt} = Y_{jt}^*(1 - G_{jt})$ to obtain ($\widehat{\cdot}$ denotes a log change):

$$\widehat{Z_{jt}} \equiv \widehat{Y_{jt}} - \alpha_{K,jt}\widehat{K_{jt}} - \alpha_{M,jt}\widehat{M_{jt}} - \alpha_{L,jt}\widehat{L_{jt}} = \widehat{A_{jt}} - \gamma\Delta\frac{I_{jt-1}}{K_{jt-1}}. \tag{15}$$

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 7 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 dummies) in each period when time fixed effects are not included and by 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. To sum up, combining the time-series evolution of adjustment cost parameter γ with its negative impact on I-CF sensitivity, we find further support for hypothesis H2 that the negative trend of I-CF sensitivity is caused by the increasing adjustment cost parameter.

5 Supplementary analysis

To provide an additional set of tests for hypothesis H2, we exploit the cross-sectional variation in the level of technological advancement as a proxy for capital adjustment costs. To this end, 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.

5.1 Cross-country evidence

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 least squares analysis of Moshirian et al. (2017) and complement it with the error-corrected GMM approach, to mitigate concerns associated with the measurement error in q. 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).[18] 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 five years for both sets of economies. As q is more likely

[18] 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.

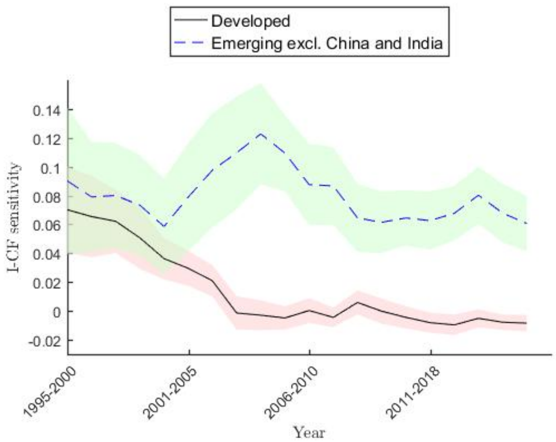
to be measured with error for this international sample, we apply an additional filter and remove the observations where its magnitude exceeds 100 or is below 0. We begin from year 1995 to ensure that there are at least 200 observations each year for each developing country. We present the estimation output using OLS, weighted least squares (WLS) with firm observations in countries with fewer (more) observations receiving greater (lower) weight by year (Moshirian et al., 2017), and Erickson-Whited errors-in-variables panel regression with highest order of moment equal to 5 (GMM5), which combines cross-sections using a minimum distance estimator (Erickson and Whited, 2000, 2002, and 2012).

The rolling-window estimated coefficients are shown in Figure 3. The decline of I-CF sensitivity for developing countries is less steep than for developed economies. Based on the OLS and WLS 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 non-decreasing trend for less developed economies is still present, albeit less pronounced, when error-corrected estimator GMM5 is used (the bottom panel of Figure 3). 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 GMM5 estimator in less developed economies fluctuates around 0.10 until almost 2003 before it experiences a slight reduction.

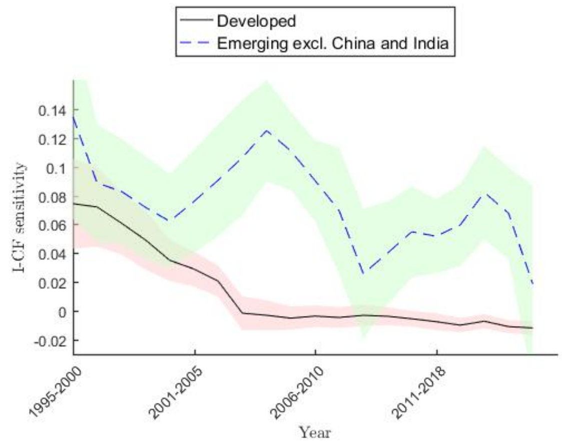
We provide an alternative to Moshirian et al. (2017) explanation for the observed difference in I-CF sensitivities between developed economies and developing economies based on the implications of capital adjustment costs. Firms in developed countries are faster in adopting the technology-intensive physical 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

FIGURE 3
Investment-cash flow sensitivity of developed economies vs. developing countries

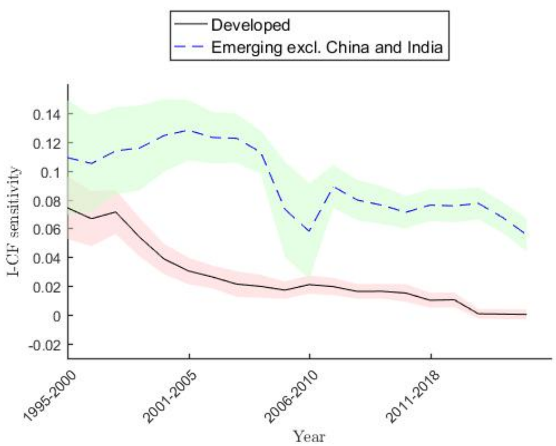
OLS



WLS



GMM5



I-CF sensitivity estimates based on the ordinary least squares (OLS), weighted least squares (WLS), and Erickson-Whited error-corrected estimator with highest order of moment equal to 5 (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.

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.

TABLE 8
Estimation across industry groups

Estimation results for the baseline I-CF regression for two industry groups. Columns 2 and 3 report coefficients of q cash flow, respectively. The results are displayed for two industry groups: non-high-tech and high-tech industries. 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.

Period	High-tech: β_1	β_2	Non-high-tech: 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

5.2 Cross-industry regression results

In the second part of the 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 have a higher proportion of technology-intensive capital compared to non-high-tech groups, we expect that the former undergo a higher rate of increase in capital adjustment costs over time and, therefore, a steeper decline in I-CF sensitivity.

Table 8 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 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

TABLE 9

Comparisons of the trend in β_2 across industry groups

Estimates of the declining trend for β_2, denoted as κ, across each industry group, i.e., non-high-tech group and high-tech group. κ is estimated by regressing β_2 on the natural log of year trend variable, which is equal to 1 for 1977, 2 for 1978 and so on. Standard errors are st statistics and corresponding p values for the null hypothesis that the declining trend is the same between high-tech and durables (nondurables) are reported. ***, **, and * indicate significance at the 1%, 5%, and 10% level, respectively.

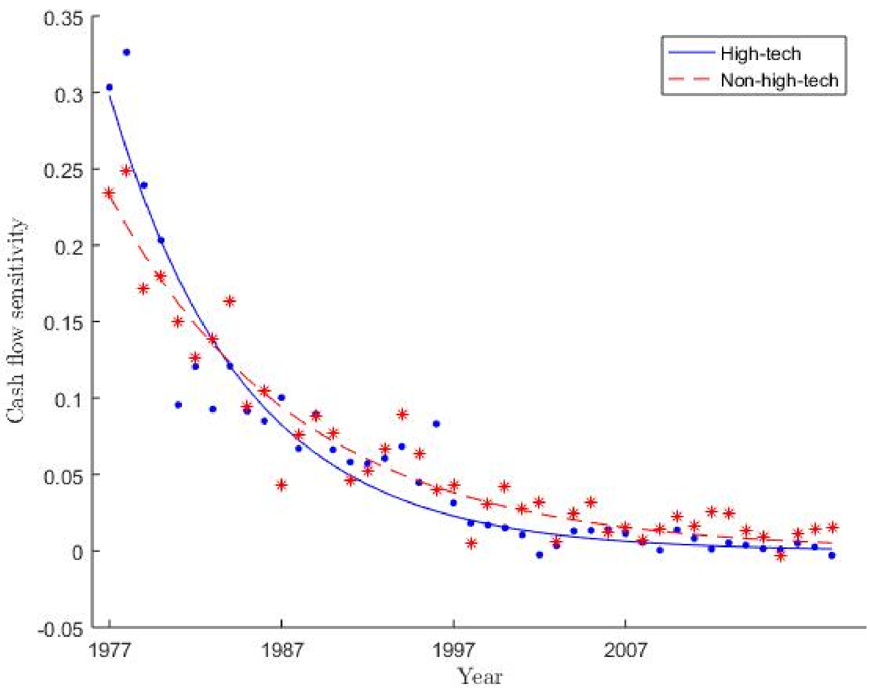
	High-tech	Non-high-tech	
κ	-0.086***	-0.070***	
	(0.004)	(0.003)	
H0: κ(High-tech)=κ(Non-high-tech)			
t stats. :	-3.005	p value:	0.000

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 the natural logarithm of β_2 on year trend variable which is equal to 1 for 1977, 2 for 1978 and so on (the corresponding regression estimates is denoted as κ). Table 9 shows that I-CF sensitivity drops by 6.7% for the non-high-tech group every year while it decreases by on average 8.6% every year for the 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 between high-tech and non-high-tech groups indicate that the declining trend of β_2 (captured by κ) is significantly more prominent for the high-tech firms than that for the non-high-tech companies.

The comparison of the declining trends is further illustrated in Figure 4 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 share of technologically advanced machinery and equipment. Also, based on the increasing adoption of ICT equipment as well as computer software (as shown in Figure 2), the lower I-CF sensitivity we observe in the later sample periods years is consistent with the fact the firms has shifted towards advanced technologies associated with higher adjustment costs.

FIGURE 4
Investment-cash flow sensitivity across groups by year (fitted with an exponential curve)

High-tech v.s. Non-high-tech



Scatter plots of investment-cash flow sensitivities estimated for high-tech (solid blue) v.s. non-high-tech (dashed red) industry fitted with an exponential curve.

6 Conclusions

The gradual decrease 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 can be expressed as a specific function of both financial constraints and capital adjustment costs, it is predominantly the evolution of the latter that is 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 sufficient 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.)

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.

A. Derivation of the profit function

To derive the profit function of the firm, consider first its production function with the Cobb-Douglas production technology:

$$F(\tilde{A}, K, L, M) = \tilde{A} K^{\alpha_K} M^{\alpha_M} L^{\alpha_L}, \tag{A.1}$$

where $\tilde{A}$ indexes technology shock, K is physical capital input, M is material input and L is labor input (with αs denoting respective elasticities). Denote the output price with p, which is given in a competitive market. p_M is price of material, and W is wage (price for labor input). With labor and material input being short-run flexible factors, the profit (operating cash flow) function can be expressed as

$$\Pi = \max_{L,M} p\tilde{A} K^{\alpha_K} M^{\alpha_M} L^{\alpha_L} - WL - p_M M. \tag{A.2}$$

Calculating the first-order condition with respect to L and M yields, respectively,

$$WL = p\alpha_L \tilde{A} K^{\alpha_K} M^{\alpha_M} L^{\alpha_L}, \tag{A.3}$$

$$p_M M = p\alpha_M \tilde{A} K^{\alpha_K} M^{\alpha_M} L^{\alpha_L}. \tag{A.4}$$

After substituting the optimal L and M into profit function, one obtains

$$\Pi = AK^{\alpha}, \tag{A.5}$$

where

$$A = (1 - \alpha_M - \alpha_L)\tilde{A}^{\frac{1}{1-\alpha_M-\alpha_L}} p^{\frac{1}{1-\alpha_M-\alpha_L}} \alpha_L^{\frac{\alpha_L}{1-\alpha_M-\alpha_L}} \alpha_M^{\frac{\alpha_M}{1-\alpha_M-\alpha_L}} W^{\frac{\alpha_L}{\alpha_M+\alpha_L-1}} p_M^{\frac{\alpha_M}{\alpha_M+\alpha_L-1}}$$

and

$$\alpha = \frac{\alpha_K}{1 - \alpha_M - \alpha_L}.$$

B. Derivation of I-CF and I-q sensitivities

The derivation of the partial derivative of investment with respect to cash flow is performed as follows. First, recall the optimality condition (3):

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

Differentiating (B.1) with respect to Π/K on both sides yields

$$\gamma(\psi - 1) \left(\frac{I}{K}\right)^{\psi-2} \frac{\partial I/K}{\partial \Pi/K} + b\Phi \frac{\partial I/K}{\partial \Pi/K} - b\Phi = 0. \tag{B.2}$$

After rearranging, one obtains

$$\frac{\partial I/K}{\partial \Pi/K} = \frac{b\Phi}{\gamma(\psi-1)(\frac{I}{K})^{\psi-2} + b\Phi}. \tag{B.3}$$

Similarly, we differentiate (B.1) with respect to q on both sides to obtain

$$\gamma(\psi-1)\left(\frac{I}{K}\right)^{\psi-2}\frac{\partial I/K}{\partial q} + b\Phi\frac{\partial I/K}{\partial q} = 1. \tag{B.4}$$

This can be expressed as

$$\frac{\partial I/K}{\partial q} = \frac{1}{\gamma(\psi-1)(\frac{I}{K})^{\psi-2} + b\Phi}. \tag{B.5}$$

C. I-CF sensitivity with non-convex and convex capital adjustment costs

As, e.g., in Whited (2006), one can consider the fact that investment incurs fixed (non-convex) adjustment costs. Assume that the adjustment cost are proportional to the capital stock and equal fK. The fixed costs only occur during periods of active investment. As stated in Cooper and Haltiwanger (2006), the fixed costs reflect the needs for restructuring and retraining of the activities and therefore they only take place when new investment is made. The firm value $V(A_t, K_t)$ can therefore be written as

$$V(A_t, K_t) = \max\{V^a(A_t, K_t), V^n(A_t, K_t)\}, \tag{C.1}$$

in which $V^n(A_t, K_t)$ ($V^a(A_t, K_t)$) reflects the firm value when no (active) investment is made. The corresponding Bellman equations are

$$V^a(A_t, K_t) = \max_{I_t}[(\Pi(A_t, K_t) - I_t - fK - G(I_t, K_t) - H(X_t, K_t)) + \theta E_{A_{t+1}|A_t}V(A_{t+1}, K_{t+1})], \tag{C.2}$$

and

$$V^n(A_t, K_t) = [\Pi(A_t, K_t) + \theta E_{A_{t+1}|A_t}V(A_{t+1}, (1-\delta)K_t)]. \tag{C.3}$$

All relevant parameters are as defined before. The first-order condition when active investment is made is

$$1 + \gamma\left(\frac{I_t}{K_t}\right)^{\psi-1} + b\Phi\left(\frac{I_t}{K_t} - \frac{\Pi_t}{K_t}\right) = q_t, \tag{C.4}$$

where $q_t = \theta E_{A_{t+1}|A_t}V^a_K(A_{t+1}, K_{t+1})$. Define $\mathbf{1}(I > 0)$ as an indictor of investment being made. I-CF sensitivity can now be derived:

$$\frac{\partial I/K}{\partial \Pi/K} = \frac{b\Phi}{\gamma(\psi-1)(\frac{I}{K})^{\psi-2} + b\Phi}\mathbf{1}(I > 0). \tag{C.5}$$

It can be seen that a fixed cost of capital adjustment influences I-CF sensitivity by affecting the probability of making active investment (or, the expectation of the indicator function). A higher fixed cost f reduces the probability of investment (and the mean value of $\mathbf{1}(I > 0)$) and leads to a *lower* I-CF sensitivity *in expectation terms*.

D. Euler investment equation: The 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:

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

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

$$\begin{aligned} \mathcal{L} &= \max_{\{K_{\tau+1}, I_\tau\}_{\tau=t}^{\infty}} E_t \sum_{\tau=t} \left(\frac{1}{1+r}\right)^{\tau-t} [\Pi(A_\tau, K_\tau) - I_\tau - G(I_\tau, K_\tau) \quad &\text{(D.2)} \\ &\quad -H(X_\tau, K_\tau) + q_\tau(I_\tau + (1-\delta)K_\tau - K_{\tau+1})], \quad &\text{(D.3)} \end{aligned}$$

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

$$\frac{\partial \mathcal{L}}{\partial I_t} = 0 \Rightarrow q_t = 1 + \frac{\partial G(I_t, K_t)}{\partial I_t} + \frac{\partial H(X_t, K_t)}{\partial I_t}, \quad \text{(D.4)}$$

$$\begin{aligned} &\frac{\partial \mathcal{L}}{\partial K_{t+1}} = 0 \Rightarrow \quad \text{(D.5)} \\ &q_t = \frac{1}{1+r} E_t \left[(1-\delta) q_{t+1} + \frac{\partial \Pi(A_{t+1}, K_{t+1})}{\partial K_{t+1}} - \frac{\partial G(I_{t+1}, K_{t+1})}{\partial K_{t+1}} - \frac{\partial H(X_{t+1}, K_{t+1})}{\partial K_{t+1}}\right]. \end{aligned}$$

With the iterative substitution of (D.5) and the transversality condition which requires that $\lim_{T\to\infty} q_{t+T}/(1+r)^{t+T} = 0$, we obtain

$$q_t = E_t \sum_{\tau=t+1}^{\infty} \frac{(1-\delta)^{\tau-t-1}}{(1+r)^{\tau-t}} \left(\frac{\partial \Pi(A_\tau, K_\tau)}{\partial K_\tau} - \frac{\partial G(I_\tau, K_\tau)}{\partial K_\tau} - \frac{\partial H(X_\tau, K_\tau)}{\partial K_\tau}\right). \quad \text{(D.6)}$$

The substitution of (D.4) into (D.5) yields

$$\begin{aligned}
&1+\frac{\partial G(I_t,K_t)}{\partial I_t}+\frac{\partial H(X_t,K_t)}{\partial I_t}=\\
&\frac{1}{1+r}E_t\left[(1-\delta)\left(1+\frac{\partial G(I_{t+1},K_{t+1})}{\partial I_{t+1}}+\right.\right.\\
&\left.\left.\frac{\partial H(X_{t+1},K_{t+1})}{\partial I_{t+1}}\right)+\frac{\partial \Pi(A_{t+1},K_{t+1})}{\partial K_{t+1}}-\frac{\partial G(I_{t+1},K_{t+1})}{\partial K_{t+1}}-\frac{\partial H(X_{t+1},K_{t+1})}{\partial K_{t+1}}\right]. \qquad \text{(D.7)}
\end{aligned}$$

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 $\partial H(X_t,K_t)/\partial K_t = -0.5b\phi\left(I_tK_t - \Pi_t/K_t\right)\left(I_tK_t + \Pi_t/K_t\right)$. 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:

$$\begin{aligned}
&\frac{1}{1+r}\left[(1-\delta)\left(1+\gamma\left(\frac{I_{t+1}}{K_{t+1}}\right)+b\phi\left(\frac{I_{t+1}}{K_{t+1}}-\frac{\Pi_{t+1}}{K_{t+1}}\right)\right)+\right.\\
&\left.\frac{\Pi_{t+1}}{K_{t+1}}+\frac{1}{2}\gamma\left(\frac{I_{t+1}}{K_{t+1}}\right)^2+\frac{1}{2}b\phi\left(\frac{I_{t+1}}{K_{t+1}}-\frac{\Pi_{t+1}}{K_{t+1}}\right)\left(\frac{I_{t+1}}{K_{t+1}}+\frac{\Pi_{t+1}}{K_{t+1}}\right)\right]+\epsilon_{t+1}\\
&=1+\gamma\left(\frac{I_t}{K_t}\right)+b\phi\left(\frac{I_t}{K_t}-\frac{\Pi_t}{K_t}\right). \qquad \text{(D.8)}
\end{aligned}$$

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