Financial Regulation, Pension Investment, and Economic Growth

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Abstract

This paper analyses how financial regulation that reduces investors' willingness to take risk impacts economic growth. I study a regulatory reform that tightened risk requirements on British pension funds and led to a large divestment from equity markets. To leverage the reform as a natural experiment, I collect and digitise new security-level holdings data for a large fraction of the pension sector. I then study how pension funds' equity sales affected firms' investment decisions. I show that firms more exposed to pension investors before the reform experienced a persistent fall in stock prices and a rise in risk premia. In response, these firms cut their capital and R&D expenditure and reduced the share of long-term investment. Motivated by these findings, I introduce a new growth framework that combines Schumpeterian growth with segmented equity markets. A limited number of risk-averse investors hold stocks in incumbent firms who invest in risky innovation. Limiting the risk-taking capacity of a subset of investors not only raises the market risk premium and reduces incumbent R&D, but also spills over to market entry in general equilibrium. When the rise in the risk premium is sufficiently strong, entry falls. Quantitative simulations suggest that pension schemes' equity sell-off, which was equivalent to approximately 3 percent of market capitalisation, generated a 0.14 percentage-point drop in annual growth.

Keywords: Growth, financial markets, financial regulation, innovation, pension funds.
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1 Introduction

Since the Global Financial Crisis, economic growth in many advanced economies has stalled. An often-cited explanation for this slowdown is that the tightening of financial regulation post-crisis has made investors reluctant to fund risky investments that drive growth (e.g. Cochrane, 2020; Draghi, 2024). While a large literature has studied how regulation shapes investors' incentives to take risk (e.g. Admati and Hellwig, 2013; Dewatripont et al., 2010), our understanding of how these policies affect growth is much more limited.

From a macroeconomic point of view, an important dimension is the effect of financial regulation on the price and supply of capital to firms. When capital markets are imperfect and there are limits to arbitrage, for example due to segmentation (Gromb and Vayanos, 2010; Shleifer and Vishny, 1998) or inelastic demand (Gabaix and Koijen, 2021), tighter regulation on market participants' risk-taking capacity can decrease market valuations, increase firms' cost of capital, and thus reduce their scope to invest. If these shifts are large and persistent, financial regulation may have unanticipated consequences for growth.

In this paper, I study empirically and theoretically how regulation that reduces investors' willingness to take risk impacts economic growth. The paper is structured around three contributions. First, I study the impact of a particular example of such regulation, a reform in the United Kingdom that tightened risk requirements on pension funds and led to a large divestment from equity markets. To leverage the reform as a natural experiment, I collect and digitise a new dataset that contains security-level stock holdings for a large share of British pension funds over the last 20 years. Consistent with the limits to arbitrage view of capital markets, I show that firms more reliant on pension investors saw a persistent fall in stock prices. In response, these firms cut back on their long-term investment. Second, I take this evidence as motivation to introduce a new endogenous growth framework with segmented equity markets and risk-averse investors. I use this model to study theoretically how limits to investor risk-taking capacity affect firms' investment incentives, and how, in general equilibrium, they shape firm dynamics and growth. Third, I calibrate the model to quantify how the tightening of risk requirements on pension funds has affected economic growth. The quantitative model suggests that the decline in pension equity investment lowered the U.K.'s annual growth rate by 0.14 percentage points, which is equivalent to a potential output loss of 5.4 percent over the twenty years following the reform.

The paper starts by providing empirical evidence on the impact of pension investment on firm outcomes. The setting is a natural experiment in the United Kingdom, where the collapse of a large corporate pension scheme in the late 1990s prompted the government to tighten risk requirements on defined-benefit pension schemes. Under the Pensions Act 2004, the regulator was tasked with monitoring schemes' *funding level*, defined as the difference between the market value of assets and future pension obligations. The present value of these obligations was to be calculated using yields on inflation-linked gilts. Since a deterioration of their funding level could trigger regulatory intervention, the reform incentivised schemes to sell equities and buy long-maturity bonds, thus reducing both the volatility of their assets and duration risk from their long-dated liabilities. Within three years of the reform, pension funds sold more than £65bn in equities. Using cross-sectional data on pension schemes' funding level, I show that schemes with lower funding levels pre-reform subsequently sold a larger proportion of their equity holdings.

Building on these findings, I use the reform as a natural experiment to analyse how pension funds' withdrawal from equity markets influenced the investment decisions of those non-financial firms that the funds were previously invested in. This analysis requires a panel of pension funds' stock holdings matched with firm balance sheet and earnings data from at least 2002, when the reform was announced. Given that such a dataset does not exist, I construct it from scratch using financial holdings, annual reports, and valuation reports for 100 public-sector pension schemes in the U.K., which were obtained through *Freedom of Information* requests. To construct stock holdings, I use a multi-stage matching procedure which allows me to also infer holdings managed by external asset managers. I then merge the fund data with firm-level financials and balance sheet data. The final dataset covers 40 percent of the defined-benefit pension sector for the years 1999 to 2024.

The observation that more underfunded pension schemes sold larger quantities of stocks in response to the reform motivates an event-study shift-share design (Bartik, 1991). Specifically, I construct an exposure measure using the share of pension fund stock ownership in each firm as the *share* and the subsequent cumulative divestment from equities at the fund level as the exogenous *shift*. This design exploits the idea that a pension scheme's total divestment from equities is exogenous with respect to a particular firm's characteristics, although the divestment from this firm's stock is, of course, not. The underlying assumption is that the match between pension funds and firms prior to the reform is uncorrelated with differences in post-reform firm outcomes, after controlling for observables. I provide evidence for this assumption using three strategies. First, return regressions show that the cross-sectional variation in funding levels was driven by the performance of U.K. equities. After controlling for equity exposure, past returns are not predictive of funding levels. Second, measures of portfolio composition show that within equities, there is little compositional variation, as pension funds closely track the benchmark. Third, I corroborate my results using an alternative instrument based on schemes' membership structure, which leverages the idea that schemes with a higher ratio of pensioners to contributors should be more underfunded because of higher future pension obligations and therefore should react more sensitively to the tighter funding requirements.

My empirical analysis finds a negative effect of pension capital withdrawal on firm outcomes. I estimate that a one percentage point reduction in pension fund equity investment reduces stock prices by 0.45 percent after one year, implying that the divestment was only partially offset by other investors. This has consequences for firms' real investment choices. For every one percentage point reduction in pension investment, firms cut their capital and R&D expenditure by 1 percent and 1.2 percent, respectively, and pivot towards more short-term investments. Here, an additional one percentage point reduction in pension investment lowers the share of long-term investment by 0.4 percent, as proxied by the asset composition of firms' balance sheets. This investment response changes firms fundamentals and leads to a further drop in stock prices. After five years, valuations are 1.75 percent lower relative to pre-reform levels.

Motivated by the finding that the reform-driven withdrawal of pension capital had a persistent price impact and prompted firms to cut long-term investment, I theoretically explore how changes in investor risk-taking capacity affect growth. I introduce a Schumpeterian growth model with innovation by incumbents, who are funded in *segmented* public equity markets, and outside innovators, who are funded by inside equity. The model's main mechanism arises from the interaction of incumbent firms, of which there is a finite discrete number, with two types of risk-averse investors in these segmented equity markets. The first type, market-driven investors, solve a conventional portfolio problem and allocate funding based on Sharpe ratios. In contrast, liability-driven investors, who can be thought of as defined-benefit pension funds or insurance companies, solve a mean-variance problem subject to a value-at-risk constraint that limits their exposure to volatile stocks. Given investor demand, non-financial firms invest in innovation to maximise their stock price. Departing from standard Schumpeterian growth models (e.g. Aghion et al., 2014; Akcigit and Kerr, 2018), the intensity at which firms innovate is connected to the riskiness of their investment. Larger, more ambitious projects expose innovators to greater cash flow volatility, similar to liquidity shocks à la Holmström and Tirole (1998). This connection between innovation and cash flow volatility implies that higher innovation rates lead to more volatile stock prices. Because there is only a discrete number of incumbent firms, shocks to individual firms introduce aggregate risk. Risk-averse investors need to be compensated to hold stocks via a risk premium. When making their innovation decision, firms anticipate this feedback effect and adjust their innovation investment downwards compared to the desired scale with risk-neutral investors. In equilibrium, investment depends on liability-driven investors' capacity to take risk and thus their regulatory constraint.

The main comparative statics exercise is a tightening of liability-driven investors' value-at-risk constraint, similar to the 2004 pensions reform, prompting them to sell volatile stocks. For the stock market to clear, market-driven investors need to be compensated with a higher risk premium to absorb liability-driven investors' stock sales. Incumbent firms, faced with a higher risk premium and thus lower stock prices, cut back on innovation investment to reduce the magnitude of the cash flow shocks generated by large-scale investment and thus counteract the rise in risk premia. In partial equilibrium, the economy's growth rate falls. In general equilibrium, the reduction in incumbent innovation has two opposing effects on entry: While a higher risk premium reduces the value of entry for outside innovators, lower incumbent investment depresses factor prices and thus the cost of entry. Hence, whether there is more or less entry in response to a rise in risk premia depends on the relative strength of these *risk premium* and *reallocation effects*. When the former dominates, the growth rate is decreasing in market risk aversion. When the latter dominates, the relationship between growth and market risk aversion, and therefore the degree of regulation, is hump-shaped. On the left side of the hump, tighter risk requirements lead to *more* growth. Theoretically, the hump-shaped relationship between regulation and growth implies the existence of an interior optimal degree of regulation on the size of investors' equity positions. This regulation level balances the relative contribution of incumbent and entrant innovators to growth. I derive an analytical solution in terms of model primitives and show that optimal regulation rises with the productivity gap between entrants and incumbents and the size of the financial sector.

In the final part of the paper, I quantify how the British pension reform has affected growth. Because of the potentially non-monotonic relationship between risk-taking capacity and growth, the effect of the reform is ambiguous without a quantification. I therefore calibrate the model to a series of key pre-reform macro moments and the empirically estimated firm-level elasticity of R&D spending with respect to the funding shock, which is a sufficient statistic for the reaction of incumbent investment to the capitalisation level of the equity market. The calibration suggests that the reallocation effect on entry is relatively weak, and thus the empirically relevant case is the one where the growth rate is monotonically decreasing in the degree of regulation. To assess the impact of the reform, I then run the following exercise: holding constant all other parameters at their pre-reform level, I vary the tightness of the regulatory constraint to reproduce the observed decline in defined-benefit funds' equity portfolio share from 2002 to 2007. In the simulation, the growth rate falls by around 0.14 percentage points, which is equivalent to an output loss of 5.4 percent over the twenty years since the reform. Ninety percent of the decline in growth is driven by incumbent innovation with the remainder working through entry.

My quantitative results suggest that the pension reform overly tightened risk requirements on defined-benefit pension funds. The withdrawal of pension capital, in turn, not only led to lower investment by incumbent firms, but also had negative spillovers for prospective outside innovators through a *thinning out* of equity markets. While other investors demand partially compensated for pension schemes' divestment, the market response was not sufficiently elastic to fully offset the impact of the regulatory reform.

Contribution to the literature. This paper adds to four strands of literature. First, I contribute new evidence on the impact of pension funds on firms' investment decisions. A series of papers has used index-inclusion instruments to show that institutional ownership is associated with higher innovation rates at the firm level (Aghion et al., 2013; Bena et al., 2017). There is also evidence that pension investment is linked to higher productivity (Beetsma et al., 2024), patenting (Pozzoli et al., 2024), and profitability (Harford et al., 2018). While this literature mostly relies on index inclusion instruments or event study evidence after a change in ownership composition, my paper uses a natural experiment to provide plausibly causal evidence on the impact of pension fund divestment on firm outcomes. An exception here is Giannetti and Laeven (2009) who use a pension reform in Sweden to show that increased pension fund stock market participation has a positive impact on valuations and corporate governance.[1] However, they do not study the effect on firms' investment decisions, and none of the aforementioned papers analyse the impact on economic growth.[2]

Second, I document that regulation-driven changes in investor demand that have persistent effects on stock prices can, in turn, impact firms' real investment decisions. As such, I contribute to the literature on the importance of quantities for asset prices (Gabaix and Koijen, 2021; Vayanos and Vila, 2021) and on the real effects of financial market segmentation. The empirical literature has focused primarily on demand shifts in bond rather than equity markets. Selgrad (2024) finds that an increase in demand for firms' bonds through central banks' quantitative easing operations can boost capital investment. Hubert de Fraisse

[1]A common view within this literature is that stable investors, of which pension funds are one example, reduce funding uncertainty and encourage long-term investing (e.g. Derrien et al., 2013). The corporate finance literature refers to this as the *catering view* of ownership composition (e.g. Dong et al., 2012; Edmans, 2009; Edmans and Manso, 2011; Holmström and Tirole, 1993; von Thadden, 1995). Different types of shareholders alter managerial incentives and therefore investment strategies usually through investors' capacity to monitor. Different to this literature, my model does not rely on agency frictions.

[2]Different to this literature, which concentrates on the effect of pension fund investment at the *micro* level, typically through firms' governance and incentive structure, in this paper I take a *macro* view and show how regulatory-driven changes in pension fund activity in equity markets can shape economic growth through the supply and price of funding. Relatedly, Scharfstein (2018) argues that the capitalisation rate of pension funds is positively related to development of capital markets across countries. Similarly, the rise in pension investment in private markets has been credited as one of the key drivers behind the venture capital boom of the 1980s (Kortum and Lerner, 2000; Gompers and Lerner, 2001).

(2024) documents that changes in government bond supply can trigger inflows into the corporate bond market and thus allow firms to scale up their long-term investment. Similarly, Coppola (2024) and Kubitza (2025) show how insurance companies' persistent demand for long-term bonds is associated with higher prices, lower capital costs, and higher investment rates at the firm level. Finally, Koijen et al. (2024) demonstrate that financial regulation can trigger large demand-driven flows that affect firms' cost of capital.[3]

Third, I introduce a new framework linking equity markets and creative destruction.[4] In Aghion et al. (2025), we provide a model of endogenous financial frictions in a Klette and Kortum (2004) setting. See also the recent papers by Geelen et al. (2022) on leverage, Malamud and Zucchi (2019) on liquidity hoarding, Bustamante and Zucchi (2022) on the decline in real interest rates, and Akcigit et al. (2022b) on frictions in loan liquidation. The contribution of my paper is to introduce a framework that connects segmented equity markets with growth. This opens the door to analysing how creative destruction and stock prices interact in general equilibrium, which could be useful for a series of applications connecting growth and finance: On the growth side, changes in risk premia are linked to firms' innovation incentives, making the model useful to study how equity market imperfections shape innovation incentives. On the finance side, the framework endogenises valuations as functions of innovation by incumbents and entrants, who generate endogenous tail risk, which makes it possible to explore how creative destruction affects asset prices (e.g. Kogan et al., 2017) and equity premia (e.g. Barro and Ursúa, 2012).

Finally, this paper relates to the literature on the investment practices of public defined-benefit pension funds. While most of this literature has discussed the institutional details and pension scheme performance in the United States (e.g. Andanov and Rauh, 2022; Andanov et al., 2012; Brown et al., 2015; Novy-Marx and Rauh, 2009), my paper focuses on the United Kingdom. The reform examined in this paper introduced strict guidelines for calculating pension schemes' funding status, requiring assets to be marked to market and eliminating adjustments for expected future scheme performance. I contribute a new dataset on security-level asset allocation and document the changes in investment behaviour triggered by the reform. As such, my results may be informative about the impact of institutional reform, in particular for the large public pension market in the United States, where pension schemes still enjoy significant discretion in determining their funding status (Andanov et al., 2017; Giesecke and Rauh, 2023; Novy-Marx and Rauh, 2009, 2011).

[3]A large literature starting from Kaplan and Zingales (2000) and Baker et al. (2003) investigates how firms adjust their investment due to non-fundamental movements in stock prices.

[4]A parallel literature studies risk premia and growth models with expanding varieties. These models predict a monotonically decreasing relationship between aggregate risk premia and growth (e.g. Kung and Schmid, 2015), while the Schumpeterian framework in this paper implies a non-linear relationship driven by the reallocation of resources towards outsiders whose innovation is than incumbent firms'.

This remainder of this paper is structured as follows: Section 2 introduces the holdings data. Section 3 discusses the institutional setting and documents its market impact. Section 4 analyses the impact on firms' valuations and investment decisions. Based on these results, Section 5 presents the theoretical model and its comparative statics. Section 6 quantifies the effect on growth. Section 7 concludes.

2 Data

The empirical results in this paper are based on a regulatory change in the defined-benefit (DB) pension sector in the United Kingdom in 2004. I will describe the reform and its institutional background in detail in the next section after having introduced the data.

2.1 Sources

Measuring the impact of pension investment on non-financial firms' outcomes requires a dataset of pension fund stock holdings linked to firms' balance sheet and earnings information. Unfortunately, the availability of micro data on pension funds in the U.K. has been historically very limited. A particular institutional feature helps to overcome the data constraint. For historical reasons, more than a third of public-sector workers are enrolled in one of 98 *Local Government Pension Schemes* (LGPS). These LGPS, all of which are statutory DB schemes, are run by local councils on behalf of their employees and other eligible organisations, including for example local schools and charities. LGPS manage between £200bn and £400bn in assets, accounting for 40 percent of the DB industry in the U.K. See Appendix E.1 for an industry overview.

While the availability of public financial information for LGPS pre-2008 is scarce, as government entities, they are subject to *Freedom of Information* (FOI) requests under the *Freedom of Information Act 2000* (FOIA). The Act grants members of the public the right to access information held by public authorities, including local governments.[5]

The data in this paper comes from annual reports, accounts, actuarial valuation reports, and other internal financial data obtained via a total of 122 FOI requests from all 98 LGPS and the responsible government departments: the Ministry of Housing, Communities and Local Government (MHCLG), the Department for Work and Pensions (DWP), and the Government Actuary's Department (GAD). The data also includes other investment data and in particular the details of contracts with external investment managers. In most cases, it

[5]Even for annual reports the coverage can be patchy. The preparation of a standardised report became compulsory from 1 April 2008 under the *Local Government Pension Scheme (Administration) Regulations 2008*. Prior to that, many LGPS would only provide updates via the respective local council's annual report.

was possible to obtain data starting with the financial year 2000/2001. A list of sources by scheme can be found in Appendix E.1.

2.2 Construction

The objective is to construct a panel of security-level equity holdings for each LGPS between 2002 and 2023 that can be matched to firm-level income and balance sheet information. Due to the nature of the source material, the holdings data has been assembled using three primary strategies, details of which are in Appendix F.1:

1. **Direct holdings data:** A subset of LGPS provided security-level holdings data including common identifiers and valuations. In this case, only minor data cleaning was needed, and no further adjustments had to be made.

2. **Annual report data:** The appendices of a typical annual or valuation report contain stock-level holdings data. The level of detail varies between funds. Most LGPS report the value of their top-10, top-20 or top-100 domestic and overseas stock holdings. Using additional stock price data, one can trace the evolution of stock holdings over time. Although these tables provide a snapshot of holdings, they cover only a fraction of equity holdings and are most useful together with data on asset managers.

3. **Asset manager data:** LGPS typically delegate day-to-day portfolio management to external asset managers. Their annual reports disclose the name, mandate of the appointed manager, and the specific investment products or funds that the LGPS is invested in. For example, one scheme in the dataset reports an allocation of £247m to a *Hermes FTSE 350 Tracker*. This information can be used to reverse-engineer stock holdings.

   For each LGPS, I manually extract the names, mandates and amounts invested with external asset managers. The average LGPS has two or three managers, with whom they have long-standing relationships. I then match this data to asset manager and mutual fund holdings from FactSet and Morningstar using a multi-stage fuzzy-matching procedure based on asset manager and product names. In case of multiple matches, I use the description of the mandate provided in the LGPS report to determine the best match. Finally, I use the annual reports' top holdings data described above to cross-check the asset manager data. If matched correctly, the total position in a stock, say that of *British Telecom*, provided in the annual report matches the sum of the inferred positions in *British Telecom*, reconstructed via a scheme's asset management contracts.

Once the holdings data had been constructed, I merge it with firm balance sheet data from COMPUSTAT GLOBAL. Summary statistics of the final dataset are reported in Appendix F.2. In Appendix F.3, I discuss the representativeness of my dataset and show that it provides good coverage of the defined-benefit pension sector in the U.K. at the time of the reform.

3 The 2004 reform and its impact

This section describes the 2004 pensions reform and how it affected equity markets. I first summarise the main regulatory changes in Section 3.1 before discussing the impact on pension funds in Section 3.2. Appendix E.2 contains further details on pension reform in the U.K., including a summary of previous reforms and additional details of the 2004 reform that I use as a natural experiment. Appendix G.1 provides context on trends and asset allocation in the pensions industry in the 1990s and early 2000s.

3.1 The Pensions Act 2004

The reform. In March 2001, after a series of failed attempts at reform in the 1990s, the *New Labour* government announced its intention to overhaul the regulation of defined-benefit pension schemes. A lengthy consultation process culminated in the Pensions Act 2004. The Act strengthened regulatory oversight and expanded the powers of the independent regulator, *The Pensions Regulator* (TPR).

The most important change was the introduction of the *Statutory Funding Objective* (SFO) for defined-benefit pension schemes in Section 222 of the Act. Under the SFO, the ratio of a pension scheme's assets to the discounted value of its future pension obligations would serve as the indicator of a scheme's financial health. If this *funding level*, formally defined as:

$$\mathcal{F}_t = \frac{\text{Market Value of Assets}}{\text{Present Value of Future Pension Obligations}}, \tag{3.1}$$

would take a value less than one, a pension scheme was to be treated as *underfunded*. That is, it would not be in a position to cover its obligations were they to fall due today.[6]

The formula in (3.1) rests on two technical assumptions that were not provided for in the Act: first, whether the market environment should be factored into the calculation of

[6] The motivation for the reform was to gain an accurate picture of funding levels in the defined-benefit sector at current market prices, which would help identify systemic deficits and root out risk-taking in the industry seen by many as excessive (e.g. Myners, 2001). In contrast, Giesecke and Rauh (2023) discuss how U.S. DB pension schemes base their discount rates on expected returns, which naturally implies higher funding levels relative to risk-free rates and may belie systematic deficits due to risky investment practices.

asset values; and second, which discount rate ought to be applied when calculating the present value of future pension obligations. Under the provisions of the Act, the authority to determine the appropriate valuation methodology was delegated to TPR. The details were to be set out in a regulatory directive. The provisions took effect on 1 April 2005 with the start of the financial year 2005/2006.

The TPR directive. In June 2005, the regulator published its directive on the interpretation and enforcement of the SFO (The Pensions Regulator, 2005). In the document, TPR clarified how it would evaluate pension funds' financial position as defined in (3.1):

1. When determining the market value of assets, only the current actuarial valuation of assets would be used. Current asset composition and investment strategies would *not* be taken into account when measuring fund deficits and mitigating factors such as recent equity market under-performance would not favourably affect valuations.

2. The relevant discount rate to calculate the present value of future obligations would be tied to the yield on long-dated, index-linked gilts but would not take into account expected returns on equity investments.[7]

3. Pension funds that were seen to be in bad financial health, for example due to a quick deterioration of their funding level, would be subject to regulatory intervention. Even for funds that were projected to close their deficits, the existence of a long recovery period itself would be seen as a trigger for regulatory intervention. As a measure of last resort, the regulator reserved the right to close down schemes and transfer their assets into a master fund.

Timing of events. The government first announced its intention to reform defined-benefit pension schemes in 2001 with the publication of the Myners report (Myners, 2001). The reform proposal was first circulated as a government *White Paper* on 11 June 2003 (Department for Work and Pensions, 2003). Draft legislation was introduced as the *Pensions Bill* by the Pensions Secretary on 10 February 2004 (Lourie et al., 2004). The Bill was passed by both Houses over the summer and received Royal Assent on 18 November that year, thus

[7] To be precise, TPR outlined that it would use the so-called *Section 179 Deficit* (PPF Levy) rather than the accounting deficit under FRS17/IAS19 for its assessment of scheme funding status. FRS17/IAS19 deficits are based on AA yields to discount liabilities and take into account estimates for salary, inflation and future equity returns. Contrary to that, the Section 179 Deficit approach uses the market value of fund assets and discounts future liabilities at the relevant index-linked gilt rate at -50 basis points. The deficit is then calculated as the ratio of assets over the net-present value of liabilities.

becoming the Pensions Act 2004. The provisions took effect on 1 April 2005, and the regulator's directive was published in June of that year. Throughout this paper, I will treat the financial year 2002-2003, which ends on 31 March 2003, as the baseline pre-reform year.

3.2 Consequences

Effects on investment strategies. The regulator's interpretation of the SFO and the proposed methodology had an immediate effect on DB funds' investment strategies. Three aspects are particularly important. First, marking equity positions to market without accounting for macroeconomic conditions implied that DB pension funds with large equity position would experience fluctuations in their funding levels due to short-run movements in stock prices. As discount rates would not be adjusted for expected returns, the liabilities of an all-equity fund would be discounted at the same rate as those of an all-bond fund. These changes introduced substantial regulatory risk for funds with large equity positions.

Second, because the discount rate was tied to the yield at the long end of the gilts market, any movement in long-term rates would directly affect the present value of future pension obligations (3.1). Funds with a duration mismatch between assets and liabilities became exposed to mechanical fluctuations in their funding levels. Buying long-dated gilts or the fixed leg of an interest rate swap could be used to hedge that duration risk.

Third, after a series of macro shocks in the late 1990s and early 2000s, the SFO came into effect during a period of low equity valuations and falling interest rates. In early 2004 the yield on the 30-year gilt stood at just under 4 percent, less than half its 1998 level. This timing coincidence made the first two issues even more pressing. Because of their losses in equity markets, in particular between the financial years 2001 and 2002, almost all DB schemes were underfunded as per the regulator's definition of the SFO. Figure 3.1 provides an overview of the distribution of funding levels in 2004.

The directive was met with apprehension in the industry. At the time, it was variously described as a "*shot across the bows*" (Cohen, 2006) and "*exceedingly bearish*" for pension schemes (Barclays Capital Research, 2006). As I will show in the next section, pension funds reacted by selling equities and buying long-dated gilts. My identification strategy in Section 4 will exploit that pension schemes with lower funding levels prior to the reform were more affected by the funding requirements and therefore sold larger quantities of stocks.

Withdrawal from equity markets. Figure 3.2 shows pension schemes' cumulative purchases by asset class from 2003 to 2006. Over this period, pension funds sold £40bn in equities and shifted towards gilts and derivatives, predominantly interest rate swaps at long

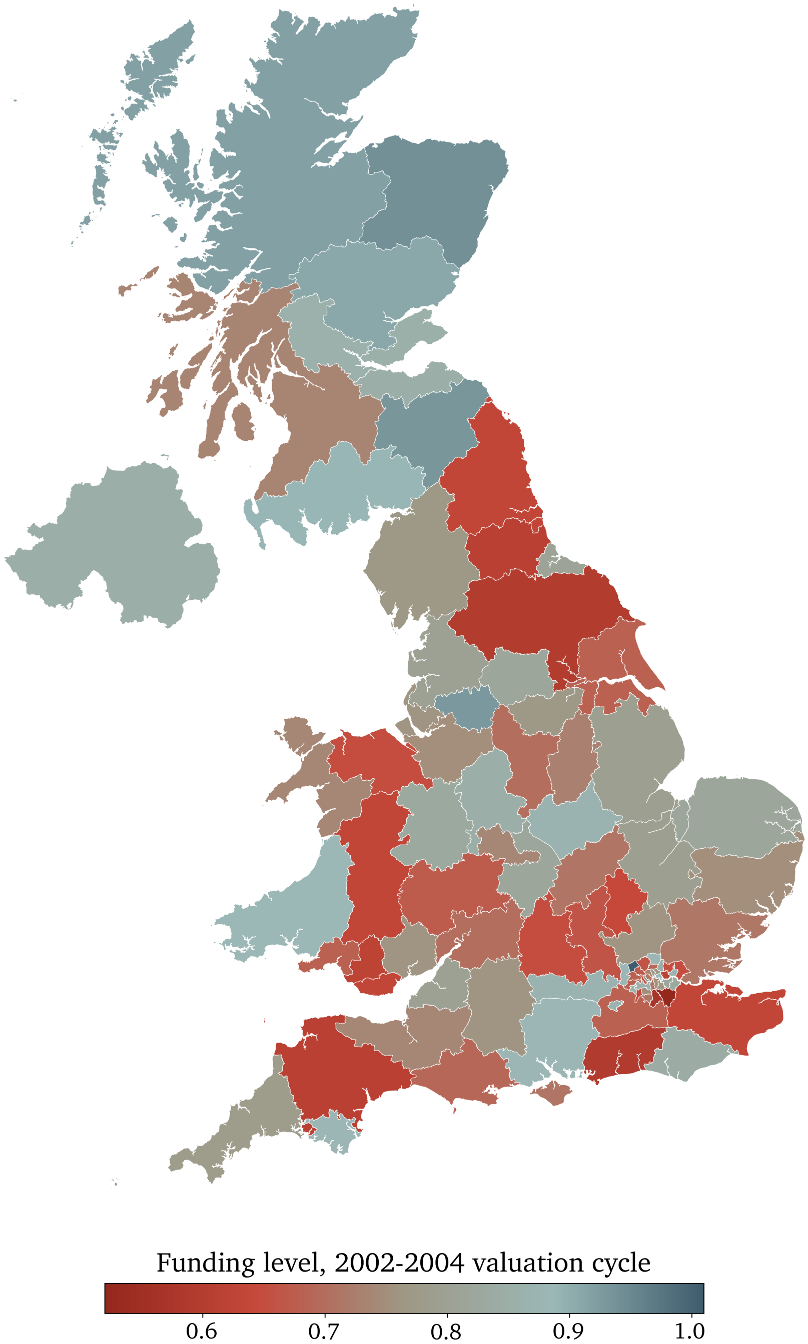

Figure 3.1: Distribution of funding levels.

The figure shows the distribution of funding levels across local government pension schemes (LGPS) for the 2002 to 2004 valuation cycle, which concluded on 31 March 2004. If multiple valuations are available, the latest valuation has been used in the figure. Darker areas reflect lower funding levels. A funding level of less than one indicates that the LGPS was underfunded as defined under the SFO. An enlarged map for London can be found in Appendix F.2.2.

maturities (Greenwood and Vayanos, 2010; Islam, 2007). Equity sales rose to £65bn by mid-2007, see Appendix G.2. The timing of the sales aligns with the passage of the pensions bill, which then accelerated with the release of the regulatory directive in 2005. Appendix G.1.1 documents that during this period the average portfolio share of U.K. equities on defined-benefit schemes' balance sheets fell from 47 percent in April 2002 to 36 percent in April 2007.[8]

Equity sales during this period were limited to pension funds. Other large institutional investors, such as life insurance companies, did not reduce their exposure to equities. As insurers and DB pension funds both face long-dated liabilities, both investor types are sensitive to the funding risk due to movements in long-term interest rates. As I show in Appendix G.2, insurance companies increased their exposure to U.K. equities during that period, while a shift into fixed income markets did not occur.

The absence of equity sell-offs among large insurance companies supports the view that the patterns in the DB sector were driven by the pensions reform rather than a change in macroeconomic conditions, which happened to coincide with the announcement or implementation of the reform. This view is also reflected in the investment reports that major banks were circulating at the time, which I have drawn on to reconstruct the timing and impact of the Pensions Act 2004 (e.g. Barclays Capital Research, 2005, 2006; Islam, 2007).

The importance of regulatory risk. Why did pension funds start to sell U.K. equities after the implementation of the pension reform? Given the particularities of the SFO, holding large quantities of equities would expose pension schemes to large fluctuations in their funding ratios. In fact, the general perception at the time was that U.K. equities in particular exposed pension funds to too much volatility in their funding levels under the SFO relative to expected returns (Barclays Capital Research, 2006).

Although there was considerable variance in investment strategies prior to the reform – some funds, such as Croydon, held more than 75 percent of their assets in domestic equity markets, while others such as Greater Manchester were much more diversified – the shift out of equities in response to the reform occurred across pension funds, and so one may expect that other factors played a role in the aggregate divestment. However, if the sell-off was driven by changes in risk-taking capacity, one would expect schemes with lower funding levels prior to the reform, who would be more likely to be investigated under the new regulation, to decrease their equity holdings by more than schemes with relatively higher funding levels.

[8]Appendix G.1.2 shows that the decline was driven by quantities rather than prices. If equity valuations had remained stable, the decline in the equity portfolio share would have been even larger than observed.

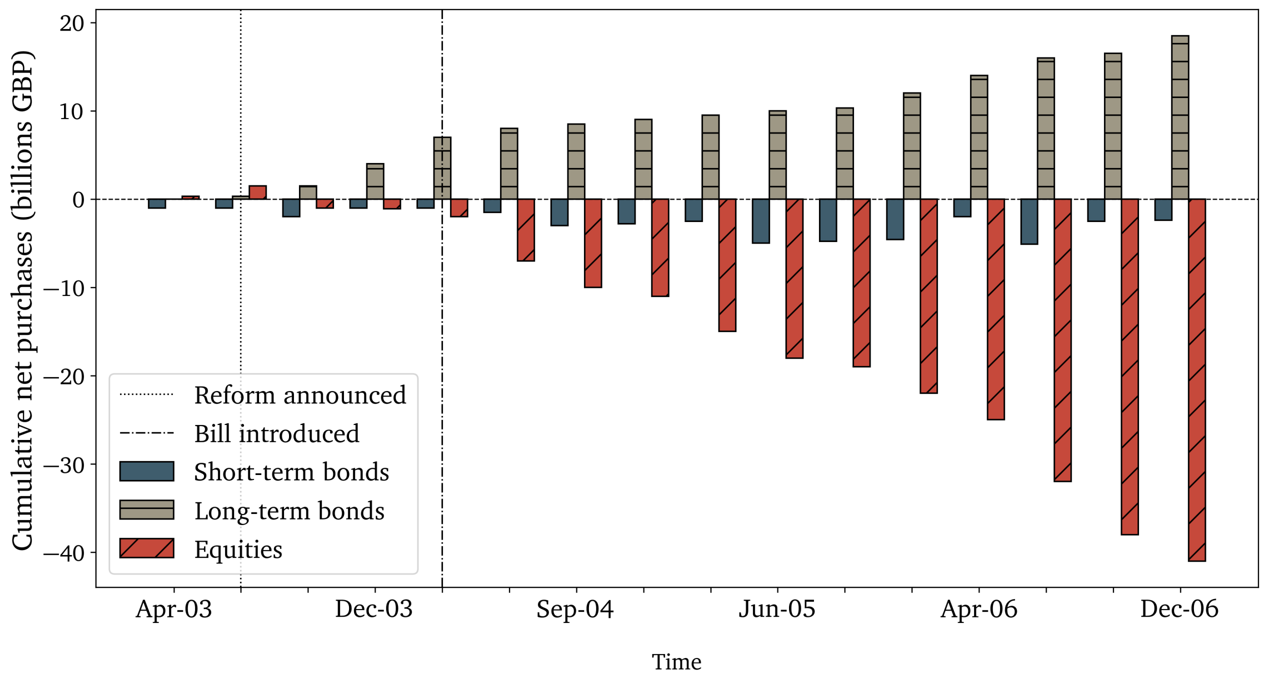

Figure 3.2: Pension fund cumulative net purchases, 2003-2006.

Flows are shown at current market prices at the time of sale and are cumulated across months. Red bars refer to equities, blue and beige bars to bonds. The omitted category is interest rate derivatives.

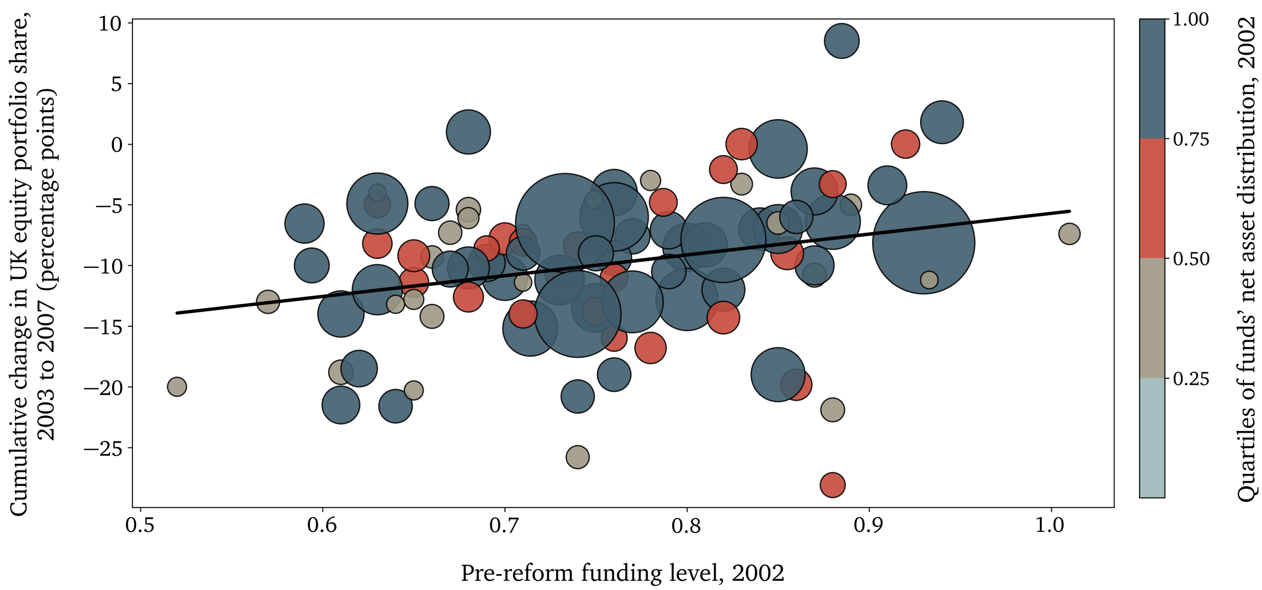

Figure 3.3: Pension fund changes in U.K. equity share.

Bubble sizes capture fund size by net assets in 2002. Colours correspond to quartiles in the net asset distribution of funds. The line of best fit comes from a regression in (3.2).

A particular feature of a previous reform, the Pensions Act 1995, allows me to test this hypothesis directly. The Act required defined-benefit pension funds to commission a triennial fund valuation with an accredited actuary. These valuation reports contain a detailed projection of future pension obligations and an official estimation of each scheme's funding level. The latest valuation cycle prior to the announcement of the Pensions Act 2004 was completed in April 2002. To test whether the pre-reform funding status is indeed predictive of the following divestment from equity, I run the following regression at the fund level:

$$\Delta\,(\text{UK Equity Portfolio Share})_{i,2007-2003} = \alpha + \beta\mathcal{F}_{i,2002} + \varepsilon_i, \tag{3.2}$$

where $\mathcal{F}_{i,2002}$ is a pension scheme's funding level in 2002 as defined in (3.1). The results of regression (3.2), as reported in Table G.1 in Appendix G.3.1, confirm this hypothesis: Pension schemes that had a greater shortfall in assets compared to their discounted liabilities pre-reform reduced their equity portfolio share by more. On average, a one percentage point lower funding ratio in 2002 corresponds to a 0.2 percentage point further decrease in the equity share between 2003 and 2007. The shift out of equities was therefore particularly concentrated in pension schemes that were underfunded prior to the reform as defined under the SFO. Figure 3.3 contains a plot of the change in the U.K. equity portfolio shares against pre-reform funding levels.[9]

This differential shift out of equities based on schemes' pre-reform funding level is the main source of exogenous variation in my empirical analysis that follows in the next section: *Firms with a higher proportion of their stock held by underfunded pension schemes before the reform saw a larger sell-off of their stocks after the reform compared to other firms*. I will describe the precise empirical specification in the next section.

4 The effect of pension capital on firm performance

This part of the paper contains the main empirical results. In Section 4.1, I discuss the specification for my firm-level regressions. Section 4.2 presents the empirical results. Section 4.3 discusses potential threats to identification and provides a series of robustness exercises.

4.1 Main specification

The baseline specification is a shift-share approach, using the pre-reform firm-level share of equity held by pension funds as the *share* and subsequent fund-level equity sales as the *shift*.

[9]To show that this pattern is not driven by changes in equity prices, I rerun the analysis in Figure 3.3 with holdings normalised to 2003 prices. See column (2) of Table G.1 in Appendix G.3.1.

Shift-share instrument. Formally, let $s_{i,f,t}$ denote pension fund f's share of equity capital in firm i at time t for funds $f = 1, \ldots, F$ and let $M_{f,t}$ denote the total equity holdings of fund f on its balance sheet at time t. Then:

$$Z_{i,2002} = \sum_{f=1}^{F} \underbrace{s_{i,f,2002}}_{\text{share}} \cdot \underbrace{(\ln M_{f,2003} - \ln M_{f,2006})}_{\text{shift}}, \tag{4.1}$$

Here, $Z_{i,2002}$ can be interpreted as the average percentage reduction in pension fund stock holdings of firm i, weighted across funds f by their portfolio shares. The shift $\ln M_{f,2003} - \ln M_{f,2006}$, that is, the percentage divestment from equities, varies across pension schemes because of differences in funding levels prior to the reform.

The key identifying assumption in (4.1) is that fund-level equity sales were uncorrelated with differences in firm-level outcomes post reform. Conversely, identification would be threatened if there was assortative matching between pension funds and firms prior to the reform in ways that affect the differences in post-reform firm performance. An example would be underfunded pension funds selecting on badly performing firms. In Section 4.3, I discuss these threats to identification in detail and provide a series of exercises and alternative specifications to rule out potential endogeneity concerns, including an additional instrument for pension schemes' pre-reform funding level.

The specification in equation (4.1), defines the 2001/2002 financial year (1 April 2001 to 31 March 2002) as the base year and measures the shares in (4.1) as of 31 March 2002, denoted by $s_{i,f,2002}$. As discussed in Section 3.1, draft legislation for the Pensions Act 2004 was first announced in spring 2003. Using 2002 as the base year is supported by the pension fund flow data. As shown in Figure 3.2 and Appendix G.2, pension funds began selling equities in 2003. Net quantities sold remained small until March 2004. The bulk of equity divestment occurred between autumn 2004 and autumn 2006. To avoid contamination due to the Global Financial Crisis (GFC), I use only the change in equity holdings up to March 2006 in the baseline specification.[10] Appendix G.5 contains a series of robustness checks.

Reduced-form specification. Using the instrument defined in (4.1), I estimate the effect of the 2002 reform at the firm level on some outcome variable $y_{i,2002+h}$ over some horizon h

[10]Most papers date the onset of the GFC with the Bear Stearns bailout in June 2007 (e.g. Chodorow-Reich, 2014). Even a more conservative dating, based on New Century's Chapter 11 filing on 2 April 2007, would still justify including the entire financial year 2006/2007 in the analysis.

by running local projections of the form:

$$\ln y_{i,2002+h} - \ln y_{i,2002} = \alpha_h + \beta_h Z_{i,2002} + \boldsymbol{\gamma}_h' \boldsymbol{X}_{i,2002} + \delta_{i,h} \sum_{f=1}^{F} s_{i,f,2002} + \varepsilon_{i,h}, \tag{4.2}$$

where β_h is the coefficient of interest. Note that I have defined $Z_{i,2002}$ in (4.1) over a decrease in holdings. β_h therefore captures the *cumulative* effect of a one percentage point *decrease* in pension fund ownership of firm equity on outcome variable y in year $2002 + h$. Moreover, α_h is a horizon (time) fixed effect and $\boldsymbol{X}_{i,2002}$ is a vector of controls containing standard variables such as book-to-market ratio, market capitalisation, capital structure, cash holdings, the share of intangible capital, and firm size, proxied by total employment. The data has been winsorised at the 5th and 95th percentiles. Standard errors are clustered at the firm level. As the shares $s_{i,f,2002}$ do not sum up to one, I control for their sum as recommended by Borusyak et al. (2025). Appendix F.3.2 presents the distribution of shares.

Since (4.2) is a shift-share specification, the coefficient of interest β_h should be interpreted as a continuous difference-in-difference between two otherwise identical firms due to a change in pension fund investment exposure, that is, the differential effect of a one percentage point decrease in pension fund investment.

4.2 The effect of pension investment at the firm level

I run the regression in (4.2) for a series of outcome variables maintaining the same baseline specification. In the text below, I present the results for firms' stock prices, capital investment, and R&D. In Appendix G.4.1, I discuss the effect on returns, firms' capital structure, and a measure of investment duration.

4.2.1 Stock prices

To estimate the impact of pension funds' withdrawal from domestic equity markets on valuation, I first run (4.2) using firms' stock prices as the dependent variable. Figure 4.1 shows the cumulative log-change in stock prices relative to the baseline year 2002 before the announcement of the pensions reform. The vertical line indicates the announcement of the reform. As Figure 4.1 shows, there are no significant pre-trends before 2002.

The results suggest that a reduction in pension fund investment is associated with a decrease in stock prices for firms more exposed to pension investment. An additional one percentage point reduction in pension fund equity holdings leads to a 0.5 percent decrease in stock prices one year after the reform. Five years after the shock, stock prices are a further percentage point lower. As I show in the next section, this further drop in stock

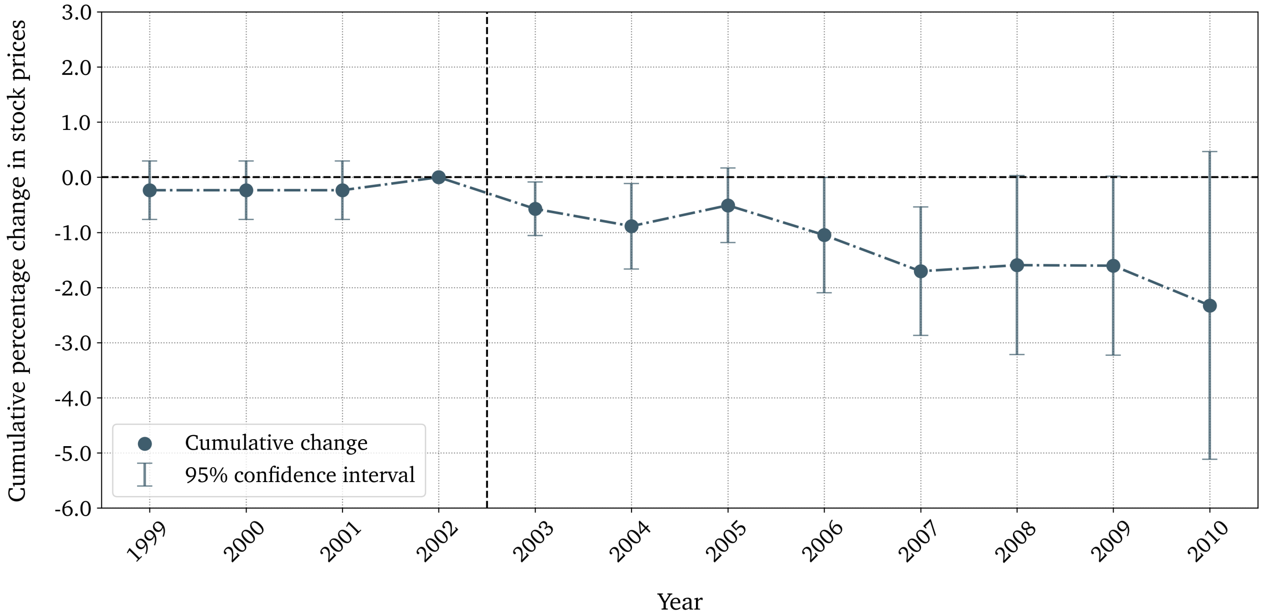

Figure 4.1: Effect on stock prices.

The figure shows the cumulative effect of a one percentage point differential reduction in pension fund equity ownership at horizon h as captured by β_h in equation (4.2). The dependent variable is the end-of-year stock price.

prices could possibly be driven by changes in firms' fundamentals driven by their reaction to the reduction in valuations.

Pension capital withdrawal has a persistent impact on firm valuations. In a frictionless capital market, one would not expect sales by pension funds to influence prices over such long horizons, since other investors should step in to stabilise prices. These results are consistent with a limits to arbitrage view of equity markets under which pension fund divestment is not fully offset by other investors leading to the reduction in market prices for firms more exposed to the shock (Shleifer and Vishny, 1998; Gromb and Vayanos, 2010), and with the related idea that markets are inelastically reacting to demand-driven flows (Gabaix and Koijen, 2021). I show in the next section how these price effects altered firms' investment decisions. I first discuss the impact on capital investment and then on R&D.

4.2.2 Capital expenditure

Figure 4.2 presents the results of regression (4.2) using capital expenditure over lagged assets as the dependent variable. This regression is meant to capture firms' investment intensity. The results suggest that a reduction in pension fund equity holdings reduces long-term capital investment. Specifically, an additional one percentage point decrease in pension fund equity holdings is, on average, associated with a one percent decrease in

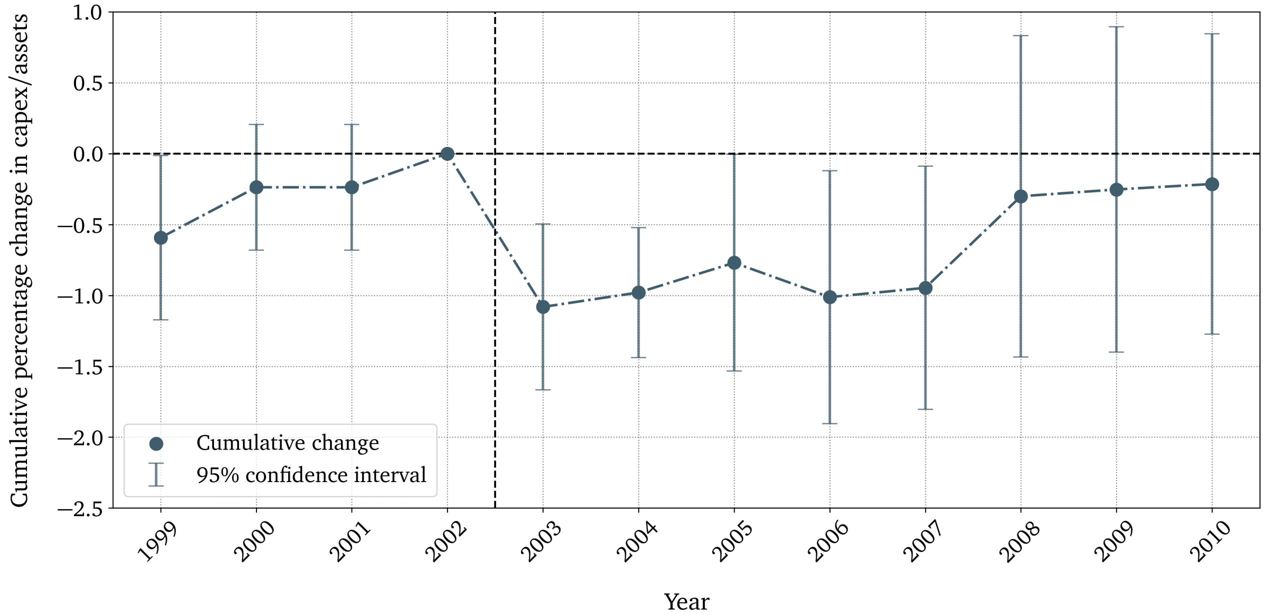

Figure 4.2: Effect on capital expenditure.

The figure shows the cumulative effect of a one percentage point differential reduction in pension fund equity ownership at horizon h as captured by β_h in equation (4.2). The dependent variable is capital expenditure over lagged assets $capex_h/assets_{h-1}$.

capital expenditure after one year. This effect persists over five years later before washing out at the longer horizon.[11]

4.2.3 Innovation

To capture firms' innovation intensity, I use their annual research and development (R&D) expenditure over lagged assets as a proxy. In most growth models, higher rates of R&D spending lead to higher innovation rates and are the key indicator of firms' innovation efforts (Aghion et al., 2014). Figure 4.3 presents the result of a regression of the form (4.2) with R&D spending over lagged assets as the dependent variable.

I find evidence that a decrease in pension investment is associated with a lower rate of innovation expenditure. An additional one percentage point reduction in pension fund equity holdings, on average, leads to a 1.2 percent reduction in R&D expenditure over assets at the five-year horizon, which falls further to around 2 percent eight years after the reform. The slow-moving nature of R&D explains why effects only materialise two to three years after the initial shock as firms typically budget innovation spending in multi-year plans.

[11]These findings are in line with the empirical literature which has documented that changes in stock prices due to secondary market trading can have significant effects on firms' long-term investment (e.g. Bond et al., 2013, for a survey).

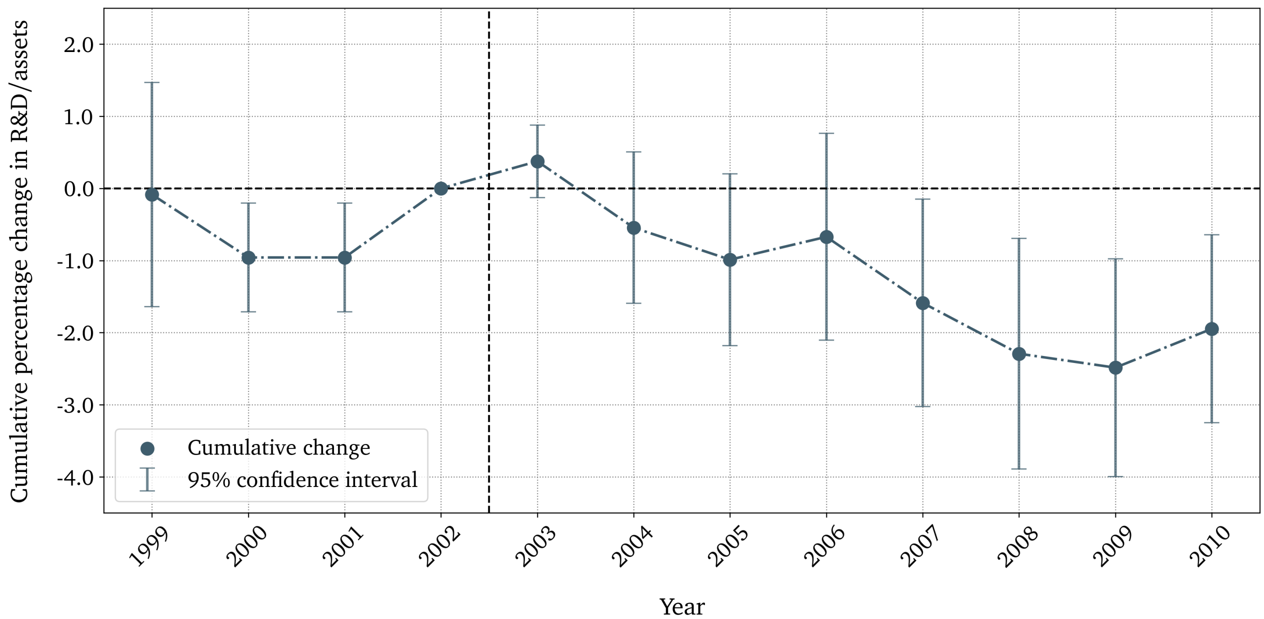

Figure 4.3: Effect on R&D expenditure.

The figure shows the cumulative effect of a one percentage point differential reduction in pension fund equity ownership at horizon h as captured by β_h in equation (4.2). The dependent variable is R&D expenditure over lagged assets $R\&D_h/assets_{h-1}$.

The estimated effects are broadly in line with the literature on the impact of pension investment on innovation spending when accounting for the longer horizon and magnitude of the event study shock. Pozzoli et al. (2024), for example, estimate that having at least one pension fund investor increases firms' patenting rates by about 7 percent and the number of R&D workers by 5 percent. Using an index-inclusion instrument, Bena et al. (2017) find that a one percentage point increase in foreign institutional ownership leads to a 0.3 percent increase in R&D within a year. My results are also in line with other estimates on the impact of changes in stock prices on firms' investment decisions of equity-dependent firms (e.g. Baker et al., 2003; Dong et al., 2012).

For this result and those in the preceding sections, Appendix G.5 contains a series of standard robustness checks. In the next section, I discuss the key threat to identification and how to address it.

4.3 Addressing threats to identification

Identification in my empirical strategy comes from the exogenous shifts. As I argued above, pension fund divestment from stocks after the reform is driven by the cross-sectional variation in funding levels between pension schemes prior to the announcement of the reform.

The key identifying assumption is therefore that differences in funding levels between pension schemes are uncorrelated with differences in changes in firm outcomes, such as R&D, capital investment and stock valuations, after the reform. Conversely, identification would be threatened if underfunded pension schemes systematically invested in firms that performed worse post reform than schemes with higher funding levels.

In this section, I argue that differences in funding levels are not driven by assortative matching between pension funds and firms. The total amount of equity sales was primarily driven by two factors: on the asset side by the portfolio share of equity investment rather than the composition thereof; and on the liability side by the deterioration in the funding level due to rising future pension commitments.

Equity exposure regression. On the asset side, the consensus view at the time was that funding deficits were largely due to general macroeconomic conditions in the UK (Barclays Capital Research, 2006), and not specific to individual pension schemes' investment strategies. The downward turn nevertheless differentially affected schemes with a preference to hold large amounts of domestic equity. To test the hypothesis that funding differences were mostly driven by equity exposure rather than scheme quality, I devise the following test:

$$\mathcal{F}_{f,t} = \alpha_t + \beta\,\text{ROA}_{f,t} + \delta\,\text{UK Equity Share}_{f,t} + \boldsymbol{\gamma}'\boldsymbol{X}_{f,t} + \varepsilon_{f,t}, \tag{4.3}$$

where $\mathcal{F}_{f,t}$ is the funding level at the end of a year, $\text{ROA}_{f,t}$ is the return on assets during that year, and $\boldsymbol{X}_{f,t}$ are fund controls listed in the Appendix. If it is indeed the case that the differences in funding levels are driven by equity exposure, past returns should not be predictive after controlling for the schemes' asset composition. The results reported in Table G.2 in Appendix G.3.2 confirm this hypothesis suggesting that funding differences come primarily from the loading on equities.

Portfolio concentration. The result that the equity share is sufficient to predict the funding level is not surprising. In general, the variation in stocks held between pension schemes is low. Equity investment is concentrated around the benchmark FTSE-100 or FTSE-350. Even though some pension funds deviate from the benchmark, there is no systematic overweighting of certain stocks by funds with low funding levels prior to the reform.

Table F.2 in Appendix F.3.1 reports various measures of portfolio concentration. The standard deviation of the Herfindahl-Hirschman index of portfolio concentration, for instance, is only 0.01, indicating little variation in portfolio weights. The cosine similarity, a common measure of similarity of two vectors is on average 0.8, again indicating very high similarity between portfolios. This confirms that most variation across funds comes from equity portfolio shares rather than within-equity variation of portfolio allocations.

Membership structure. On the liability side, the key determinant of funding status is a scheme's future pension commitments and hence its membership structure. A pension scheme with few active contributors and many pensioners faces higher liabilities while collecting less in contributions. Hence, its funding level should be systematically lower. I leverage this insight in a final robustness check. As I show in Appendix G.5.4 and Figure G.5.4, funding levels across pension schemes are highly correlated with the ratio of contributors relative to pensioners. In fact, the reduction in equity investment post reform can be predicted by a scheme's pre-reform membership structure. In conjunction with the results in the previous section, this suggests that pre-reform funding levels were driven in large part by the liability side of schemes' balance sheet and their U.K. equity exposure.

The results from the membership instrument regression reported in the same Appendix confirm the baseline results: Firms more exposed to pension fund investment experience a drop in stock prices, and subsequently invest less in R&D. In the next section, I will explore the implications of these results in a general equilibrium growth model.

5 A model of pension investment and growth

The results so far show that the withdrawal of pension capital triggered by the pension reform has had a significant negative effect on stock valuations, and subsequently on investment and R&D at the firm level. As the aggregate impact on growth cannot be identified using firm-level estimates, a general equilibrium model is needed. Such a model should account for the feedback between investors' asset allocation, firms' innovation investment, and market entry, the other key driver of innovation-led growth.

Section 5.1 presents the model. It combines portfolio choice with a Schumpeterian growth framework with innovation by incumbents and outsiders. I derive its equilibrium and characterise how pension funds' stock market investment affects innovation via stock prices in Section 5.2. In Section 5.3, I provide simple comparative statics of how a change in pension funds' risk-taking capacity, such as the Pensions Act 2004, affects incumbent and entry innovation. I quantify the growth effects in the final section of the paper.

5.1 Environment

Time is continuous. Let $\{\Omega, \mathcal{F}, \mathcal{P}\}$ be a probability space with filtration $\mathcal{F}_t$ capturing the information at time $t \in \mathbb{R}_+$. There are four classes of agents: households, investors, outsiders, and incumbents, the latter comprising intermediate producers and a final good firm.

5.1.1 Household

The representative household inelastically supplies L units of labour and saves in a risk-free bond. Its members discount the future at rate r and derive utility from consumption:

$$\mathrm{E}\left[\int_0^\infty \exp\left(-rt\right) dC_t \;\middle|\; \mathcal{F}_t\right]. \tag{5.1}$$

The linearity in (5.1) ensures that the household elastically supplies any quantity of the risk-free bond demanded by financial markets at the constant market clearing rate r.[12]

5.1.2 Production

The final good Y_t, the economy's numéraire, is produced in a two-stage process split between a competitive final good producer and a set of intermediate good monopolists.

Final good. The final good producer uses labour L_t^P and $i = 1, \ldots, N$ intermediate inputs, each of which comes at some quality level q_{it}. Higher-quality inputs have a higher marginal product. The production technology is represented by the nested Cobb-Douglas function:

$$Y_t = \frac{1}{1-\vartheta}\left(\sum_{i=1}^{N} q_{it}^{\vartheta} y_{it}^{1-\vartheta}\right)\left(L_t^P\right)^{\vartheta}, \tag{5.2}$$

where $1/\vartheta$ is the elasticity of substitution between different varieties of the intermediate good. If the price for input i of quality q_{it} is $\varrho(q_{it})$ and the wage is w_t, the input demand functions are:

$$y_{it} = \varrho\left(q_{it}\right)^{-\frac{1}{\vartheta}} q_{it} L_t^P \qquad \text{and} \qquad L_t^P = \frac{\vartheta Y_t}{w_t}. \tag{5.3}$$

Intermediate goods. Intermediate producers make a static and a dynamic decision. The static decision is how much to produce for a given quality level q_{it}. A producer's technology turns $1 - \vartheta$ units of the final good into one unit of an intermediate good at quality q_{it}.

[12] An equivalent interpretation is a small open economy where international investors provide capital at rate r but cannot hold domestic stocks. See Brunnermeier and Sannikov (2014, 2016) for a similar setup.

Taking demand (5.3) as given, the firm chooses its price $\varrho\,(q_{it})$ to maximise profits $\pi(q_{it})$. The problem yields a linear profit function $\pi(q_{it}) = \pi q_{it}$, where $\pi \equiv \vartheta L_t^P$. The details are in Appendix A.2.

The firm's dynamic decision involves determining how much it should invest to improve its product quality. I will discuss investment in innovation in Section 5.1.3.

Aggregation. To aggregate the production side of the economy, I define the cumulative quality level of intermediate firms as:

$$Q_t \equiv \sum_{i=1}^{N} q_{it}. \tag{5.4}$$

Appendix A.2 shows that when summing across intermediate firms, output, production costs, wages, and profits grow with Q_t. I write firms' relative quality as $\varphi_{it} \equiv q_{it}/Q_t$.

5.1.3 Intermediate firms

Innovation. The quality of an intermediate input changes over time for two reasons. First, intermediate firms innovate. Investing $\zeta z_t^{\eta} \varphi_{it}$ units of labour increases the quality level at a flow rate z_{it}. More ambitious innovation projects, which grow the firm's quality level at a faster pace, introduce more risk. The volatility $\sigma(z_{it})$ of the firm's quality is therefore increasing in the drift z_{it}.[13] Second, incumbents are at risk of creative destruction from outsiders at Poisson rate z_{it}^e. Whenever an outsider successfully innovates on a product line, quality jumps by $\nu > 1$ and the current incumbent is replaced. Combining the two sources of growth, product quality follows:

$$\frac{dq_{it}}{q_{it}} = z_{it}dt + \sigma(z_{it})d\mathcal{Z}_{it} + (\nu - 1)d\mathcal{J}_{it}, \tag{5.5}$$

where $d\mathcal{Z}_{it}$ captures quality shocks and $d\mathcal{J}_{it}$ creative destruction risk at intensity $\mathrm{E}[d\mathcal{J}_{it}] = z_{it}^e dt$. Investors demand a risk premium due to the scale of innovation projects and creative destruction risk. In the baseline model presented in this section, all risk is idiosyncratic. In Appendix B, I extend the model to allow for a common aggregate risk factor across product lines. I will now discuss how firms' decisions interact with the stock market.

[13] As profits scale linearly in q_{it}, one rationalisation of the assumption that the volatility of the quality process depends on z_{it} is that investment in innovation is risky and therefore exposes firms to liquidity shocks as in Holmström and Tirole (1998). See Aghion et al. (2010, 2025), among many papers, for a growth model in which the magnitude of liquidity shocks correlates with project size.

Stock returns. Firms' stocks are traded in a public market. When hit by creative destruction, the erstwhile monopolist ceases operations and the shareholders are wiped out. Given (5.5), I denote the price of firm i's stock by $P(q_{it})$. The return consists of the dividend yield $[\pi(q_{it}) - \zeta z_{it}^{\eta}\varphi_{it}w_t]/P(q_{it})$ plus the capital gain and the creative destruction jump. Using Itô's lemma it follows that:

$$dR(q_{it}) = \mu_{it}dt + \varsigma_{it}d\mathcal{Z}_{it} - d\mathcal{J}_{it}, \tag{5.6}$$

with the short-hand coefficients for the drift and the volatility given by:

$$\begin{aligned} \mu_{it} &\equiv \frac{\pi(q_{it}) - \zeta z_{it}^{\eta}\varphi_{it}w_t}{P(q_{it})} + \frac{P'(q_{it})z_{it}q_{it}}{P(q_{it})} + \frac{1}{2}\frac{P''(q_{it})\left[\sigma(z_{it})q_{it}\right]^2}{P(q_{it})} \\ \varsigma_{it} &\equiv \frac{P'(q_{it})\sigma(z_{it})q_{it}}{P(q_{it})}. \end{aligned} \tag{5.7}$$

5.1.4 Investors

A unit mass of investors allocates their wealth between a risk-free bond, paying r, and N uncorrelated stocks with returns given by (5.7). A share β of these investors are *liability-driven* investors, indexed by L, while the remaining $1-\beta$ are *market-driven* investors, indexed by M. One may think of the former as defined-benefit pension schemes and of the latter as retail investors. I will discuss their portfolio choice in turn.

Market-driven investors. Market-driven investors have mean-variance utility with risk aversion parameter $\tilde{\gamma}$ over instantaneous changes in their wealth level W_t^M. To ensure the model is consistent with balanced growth, I define the risk aversion parameter $\tilde{\gamma} \equiv \gamma/Q_t$ where Q_t is the aggregate quality level defined in (5.4).[14] Given portfolio holdings $\{\alpha_{it}^M\}_{i=1}^N$ for these stocks, investor wealth follows:

$$\frac{dW_t^M}{W_t^M} = rdt + \sum_{i=1}^N \alpha_{it}^M\left(\mu_{it} - r\right)dt + \sum_{i=1}^N \alpha_{it}^M \varsigma_{it}d\mathcal{Z}_{it} - \sum_{i=1}^N \alpha_{it}^M d\mathcal{J}_{it}. \tag{5.8}$$

Accordingly, each market-driven investor solves the following mean-variance optimisation problem by choosing the portfolio shares of equity:

$$\max_{\{\alpha_{it}^M\}_{i=1}^N} \ \mathrm{E}\left[dW_t^M\right] - \frac{\tilde{\gamma}}{2}\mathrm{Var}\left[dW_t^M\right] \qquad \text{s.t.} \qquad (5.8). \tag{5.9}$$

[14] This assumption ensures that investors' portfolio shares do not collapse to zero as their wealth level grows over time.

As shown in Appendix A.3.1, the solution to (5.9) is given by the demand function:

$$X_{it}^{M} = \frac{\mu_{it} - r - z_{it}^{e}}{\tilde{\gamma}\left(\varsigma_{it}^{2} + z_{it}^{e}\right)}. \tag{5.10}$$

Liability-driven investors. Liability-driven investors' portfolio choice problem parallels their market-driven counterparts'. To that, I add one additional feature meant to capture in reduced form the impact of financial regulation such as the pension fund reform studied in the empirical part of the paper.

As before, investors also hold wealth W_t^L with its law of motion mirroring (5.8). Their risk aversion is $\tilde{\gamma}$. Different to market-driven investors, liability-driven investors are subject to a penalty on large volatility in their wealth levels:

$$d\mathcal{P}\left(W_t^L; \tilde{\kappa}\right) = \tilde{\kappa} \operatorname{Var}\left[dW_t^L\right], \tag{5.11}$$

where $\tilde{\kappa} \geq 0$ parametrises the constraint's tightness. As with market-driven investors, I define the risk aversion parameter $\tilde{\gamma} \equiv \gamma Q_t$ and $\tilde{\kappa} \equiv \kappa Q_t$.[15] The penalty (5.11) can be interpreted as a value-at-risk constraint on investor net wealth limiting their exposure to volatile equity. In general, imposing a limit on portfolio volatility can be rationalised with an incentive problem, for example, a standard empire-building friction or alternative in a model with aggregate risk such as the one I present in Appendix B.[16]

Liability-driven investors have mean-variance preferences over instantaneous changes in their wealth level. They choose portfolio shares α_{it}^L for the $i = 1, \ldots, N$ stocks to solve:

$$\max_{\left\{\alpha_{it}^L\right\}_{i=1}^N} \; \mathrm{E}\left[dW_t^L\right] - \frac{\tilde{\gamma}}{2}\operatorname{Var}\left[dW_t^L\right] - d\mathcal{P}\left(W_t^L; \tilde{\kappa}\right) \qquad \text{s.t.} \qquad (5.11). \tag{5.12}$$

As shown in Appendix A.3.2, the optimisation problem (5.12) yields a demand function for each firm i's stock of:

$$X_{it}^{L} = \frac{\mu_{it} - r - z_{it}^{e}}{\left(2\tilde{\kappa} + \tilde{\gamma}\right)\left(\varsigma_{it}^{2} + z_{it}^{e}\right)}. \tag{5.13}$$

When $\tilde{\kappa} = 0$, the solution in (5.13) coincides with the portfolio share for market-driven investors in (5.10). A larger penalty reduces the share of wealth invested in stocks.

[15] Whether market-driven investors and liability-driven investors have the same coefficient of risk aversion γ does not affect the qualitative or quantitative model predictions as one can always rescale the parameter κ appropriately.

[16] In practice, defined-benefit pension schemes choose their asset allocation within pre-defined risk limits. This risk-bearing capacity is set periodically by trustees and depends both on the projected funding position and on any regulatory restrictions, such as the *Statutory Funding Objective* introduced in the Pensions Act 2004.

5.1.5 Stock price and investment

Firms invest to maximise stock prices. There are no incentive frictions related to the choice of z_{it}, which may produce a misalignment in incentives between stockholders and the firm's management.[17] To ensure balanced growth, each firm issues Q_t units of stock.

In equilibrium, investor risk aversion and the volatility of the firm's quality process give rise to a risk premium on its stock. As shown in Appendix A.5, market clearing in the stock market implies that the firm's Hamilton-Jacobi-Bellman equation for the stock price is given by the following expression:

$$\max_{z_{it}} \left\{ \begin{array}{c} \pi(q_{it}) - \zeta z_{it}^{\eta} \varphi_{it} w_t + P'(q_{it}) z_{it} q_{it} \\ + \frac{1}{2} P''(q_{it}) \left[\sigma(z_{it}) q_{it}\right]^2 - \left[r + \lambda \varsigma_{it}^2 + (1+\lambda) z_{it}^e\right] P(q_{it}) \end{array} \right\} = 0, \tag{5.14}$$

where

$$\lambda \equiv \frac{\gamma(2\kappa + \gamma)}{2\kappa(1-\beta) + \gamma}, \tag{5.15}$$

is a parameter that captures average market risk aversion. The parameter λ is a weighted average of effective investor risk aversion γ and $\gamma + 2\kappa$, where the weights are the relative shares of investors β and $1-\beta$ in the market. Note that this expression is independent of Q_t as the number of stocks issued by the firm grows over time such that the relative supply of stocks grows with the size of the economy.[18] When $\gamma = \kappa = 0$, investors are risk-neutral and (5.14) collapses to the standard expression known from other endogenous growth models.

The first line of the firm's value function (5.14) contains the dividend and the changes in the stock price due to innovation and quality fluctuations. The second line is the discounted value of the stock, including a two-part risk premium. The term $\lambda \varsigma_{it}^2$ is the risk premium component that compensates investors for stock price movements due to quality fluctuations, while $(1+\lambda) z_{it}^e$ captures the risk premium component associated with tail risk from creative destruction.

The first-order condition associated with the problem in (5.14) equates the marginal cost

[17] One rationalisation of this assumption is that the firm's management cares about the stock price, for example because compensation is tied to performance via stock options or incentive pay. A literature starting from Stein (1989) studies the feedback between innovation and the stock market. See also Aghion and Stein (2008) and Narayanan (1985). As my model does not have frictions on the firm side, maximising the stock price is equivalent to maximising the expected instantaneous return (5.6) for the average investor.

[18] Recall that investor risk aversion is $\tilde{\gamma} = \gamma / Q_t$. This assumption ensures that portfolio shares for equity do not collapse to zero as the economy grows. However, it also implies that demand grows with the size of the economy, which is why the supply must grow at the same rate to ensure that prices do not explode due to shrinking relative supply. See Appendix A.5 and also the market clearing condition 5.20 below for a derivation.

of choosing a higher drift, both in terms of the physical investment cost and the financial cost of a higher risk premium, to the resulting change in the stock price:

$$\zeta\eta z_{it}^{\eta-1}\varphi_{it}w_t + 2\varsigma_{it}^2\lambda\left[\frac{\sigma'(z_{it})}{\sigma(z_{it})}\right]P(q_{it}) = P'(q_{it})q_{it} + \frac{1}{2}P''(q_{it})q_{it}^2\sigma(z_{it})\sigma'(z_{it}). \tag{5.16}$$

5.1.6 Entry, growth, and the firm size distribution

Entry. Creative destruction comes from a large number of prospective outsiders. Entry is directed. Outsiders can invest $\psi z_{it}^e\varphi_{it}$ units of labour to innovate on a product line $i = 1,\ldots,N$ with intensity z_{it}^e. The dependence on $\varphi_{it} = q_{it}/Q_t$ reflects that it is easier to innovate on product lines that are further away from the frontier. A successful innovation attempt introduces a technology that allows the outsider to produce on line i with quality νq_{it}, which exceeds the incumbent's quality q_{it} by a step size $\nu > 1$. The outsider dislodges the incumbent and becomes the new monopolist. After successful entry, the new firm issues one unit of stock and immediately sells it to investors in an initial public offering at price $P(\nu q_{it})$. The free entry condition is:

$$z_{it}^e\mathrm{E}\left[P(\nu q_{it})\right] = \psi z_{it}^e\varphi_{it}w_t. \tag{5.17}$$

Growth. The expected growth rate of aggregate product quality is $\mathrm{E}\left[dQ_t/Q_t\right] \equiv g_t dt$. The change in the aggregate quality level itself is $dQ_t/Q_t = \sum_{i=1}^N (dq_{it}/q_{it})\varphi_{it}$. Thus, taking expectations, and using (5.5) for dq_{it}, as well as noting that $\mathrm{E}\left[d\mathcal{J}_{it}\right] = z_{it}^e dt$, yields:

$$g_t = \sum_{i=1}^{N}\left[z_{it} + (\nu-1)z_{it}^e\right]\varphi_{it}. \tag{5.18}$$

Firm size distribution. The evolution of product quality levels is governed by a standard Kolmogorov-forward equation. The details can be found in Appendix A.6.

5.1.7 Market clearing

There are three plus $2 \times N$ markets in the economy: one each for the final good, labour and the risk-free bond, as well as N markets for intermediate goods and the same number for firms' stock. The omitted market clearing conditions are listed in Appendix A.4.

Final good, intermediate goods, production labour, and bonds. The markets for the final good and the bond clear because households, whose linear utility allows for consumption to be positive or negative, are willing to borrow and lend arbitrary amounts at the risk-free rate r, equal to their discount rate. The intermediate good market clears by the first condition in (A.2).

Labour. Households inelastically supply L units of labour to the market. $\vartheta Y_t/w_t$ units of labour are used in final good production as specified in (5.3), ψz_{it}^e units as an input in entry, and $\zeta z_{it}^\eta \varphi_{it}$ for incumbent innovation by each of the N monopolists. The market clearing condition is:

$$L = \frac{\vartheta Y_t}{w_t} + \sum_{i=1}^{N} \psi z_{it}^e \varphi_{it} + \sum_{i=1}^{N} \zeta z_{it}^\eta \varphi_{it}. \tag{5.19}$$

Stocks. As for stock market clearing, each firm inelastically supplies Q_t units of stock such that the total amount of stocks outstanding grows with the size of the economy. Demand comes from $1-\beta$ market-driven investors and β liability-driven investors according to (5.10) and (5.13). The market clearing condition for stocks $i = 1, \ldots, N$ is:

$$Q_t = (1-\beta)X_{it}^M + \beta X_{it}^L. \tag{5.20}$$

5.2 Equilibrium

We can now discuss the equilibrium in this economy. I will first formally define the growth path and then derive firms' equilibrium innovation.

5.2.1 Equilibrium definition

Definition 1. *The economy is on a stochastic balanced growth path if all aggregate variables – output Y_t, consumption C_t, profits Π_t, wages w_t, and intermediate production costs Y_t^P – grow at a common expected growth rate g_t, the growth rate of aggregate quality Q_t defined in* (5.18)*; the risk-free rate is constant at r, the risk-neutral household's discount rate defined in* (5.1)*; and stock returns follow the process in* (5.6)*. Agents' optimisation problems satisfy the following conditions:*

(i) households choose consumption and savings according to (5.1)*;*

(ii) the final good firm makes zero profits. Its demand functions for $i = 1, \ldots, N$ intermediate inputs and production labour are given by (5.3)*;*

(iii) intermediate firms set prices and quantities, and earn profits according to (A.2)*; they maximise their stock price* (5.14) *by choosing the drift and volatility of their quality process* (5.5) *according to the first-order conditions* (5.16)*;*

(iv) market-driven investors maximise (5.9) subject to the law of motion (5.8) by choosing their portfolio share of each risky stock $i = 1, \ldots, N$ according to (5.10);

(v) liability-driven investors maximise (5.12) subject to a law of motion equivalent to (5.8) and (5.11) by choosing the portfolio share of stocks $i = 1, \ldots, N$ according to (5.13);

(vi) product quality follows the Kolmogorov-forward equation (A.14);

(vii) and the free entry condition (5.17) holds;

such that the markets for the final good, labour, the risk-free bond, N intermediate goods, and N stocks described by (A.7), (A.8), (A.9), (A.10), and (A.11) clear.

5.2.2 Solving for equilibrium

We can now proceed to characterising the model's equilibrium. From now on, I drop the subscripts i and t to simplify the notation and indicate that the solution is symmetric across firms.[19]

Next, I guess that the firm's stock price is linear in its quality level, $P(q) = Pq$. Equation (5.7) implies that the volatility of the quality process is $\varsigma = \sigma(z)$. The price equation (5.14), the firm's first-order condition (5.16), the free-entry condition (5.17), and the labour market clearing condition (5.19) define a system of four equations in four unknowns, the stock price P, the innovation rate z, the entry rate z^e and labour used in final good production L^P. The growth rate follows once entry and incumbent innovation have been determined. The analytical solution is described in Proposition 1 and the step-by-step derivation can be found in Appendix A.7.1.

Proposition 1. *Consider the equilibrium of the model described in Definition 1. Incumbent investment and entry rates are given by:*

$$z = \left[\frac{\phi(z)\psi}{\zeta\eta\nu}\right]^{\frac{1}{\eta-1}} \qquad \text{and} \qquad z^e = \frac{1}{\Xi}\left(\underline{z}^e - \lambda\sigma(z)^2 - \left[\frac{(2-\vartheta)\phi(z)-\eta}{\eta}\right]z\right), \tag{5.21}$$

where $\underline{z}^e \equiv (1-\vartheta)\nu L/\psi - r$ and $\Xi \equiv (1-\vartheta)\nu + 1 + \lambda$ are constants, and $\phi(z) \equiv 1 - 2\lambda\sigma'(z)\sigma(z)$ is a function of z. The equilibrium growth rate is:

$$g = \frac{1}{\Xi}\left[(\nu-1)\underline{z}^e - (\nu-1)\lambda\sigma(z)^2 + \left((2-\vartheta)\nu\left[1 - \left(\frac{\nu-1}{\nu}\right)\frac{\phi(z)}{\eta}\right] + \lambda\right)z\right], \tag{5.22}$$

[19] This also implies that the firm size distribution will not have an effect on aggregate variables as in Klette and Kortum (2004). See Appendix A.6 for further details including the Kolmogorov-forward equation.

and the market risk premium is:

$$\mu - r = (1 + \lambda)z^e + \lambda\sigma(z)^2. \tag{5.23}$$

Moreover, aggregate output is given by $Y = \frac{1}{1-\vartheta} L^P Q$ with L^P defined in (A.22).

Proof. Appendix A.7.1. □

5.2.3 Simple case

To declutter the exposition of the main comparative statics results, I will present a special case in the main text. Specifically, I impose the following functional form assumption:

Assumption 1. *The standard deviation of the quality process (5.5) takes the form $\sigma(z) = \sqrt{\underline{\sigma} z}$ with parameter values satisfying the condition $\min\left\{\frac{\eta-1}{\eta}, 1\right\} > \underline{\sigma}\lambda$.*

All results presented in the following section carry over to the general case outlined in Proposition 1. A discussion can be found in Appendix A.8.1. Under Assumption 1, the simplified equilibrium can be summarised as follows:

Lemma 1. *Consider the equilibrium described in Definition 1 and Proposition 1. If $\sigma(z) = \sqrt{\underline{\sigma} z}$, the solution is given by:*

$$z = \left[\frac{(1 - \lambda\underline{\sigma})\,\psi}{\zeta\eta\nu}\right]^{\frac{1}{\eta-1}} \qquad \text{and} \qquad z^e = \frac{\underline{z}^e}{\Xi} - \left[\frac{\zeta\nu(2 - \eta - \vartheta)}{\psi\Xi}\right] z^\eta, \tag{5.24}$$

and the growth rate is:

$$g = \frac{(\nu - 1)\underline{z}^e}{\Xi} + \left[1 + \frac{(\nu - 1)(\eta + \vartheta - 2)(1 - \lambda\underline{\sigma})}{\eta\Xi}\right] z. \tag{5.25}$$

The risk premium is given by (5.23) and output is $Y = \frac{1}{1-\vartheta} L^P Q$ with L^P defined in (A.27). As before, $\underline{z}^e \equiv (1 - \vartheta)\nu L/\psi - r$ and $\Xi \equiv (1 - \vartheta)\nu + 1 + \lambda$ are constants.

Proof. Appendix A.7.2. □

5.3 Comparative statics

I will now discuss the comparative statics of a change in liability-driven investors' risk-taking capacity, first at the firm level and then in the aggregate. One can think of this comparative statics exercise as a tightening in regulatory constraints on pension fund investment, for example the Pensions Act 2004.

Firm-level effect. Starting with the impact at the firm level, a tighter regulatory constraint κ reduces liability-driven investors' demand for stocks (5.13). This lowers prices, drives up the market risk premium, and reduces the value of investing in innovation. Firms cut back on investment. Differentiating incumbent innovation investment z:

$$\frac{dz}{d\kappa} = -\frac{\underline{\sigma} z}{(\eta-1)(1-\lambda\underline{\sigma})} \cdot \frac{d\lambda}{d\kappa} < 0, \tag{5.26}$$

or equivalently, $dz/d\kappa = -\sigma(z)^2/[(\eta-1)(1-\lambda\underline{\sigma})]d\lambda/d\kappa < 0$. The effect of a tighter regulatory constraint on liability-driven investors on firm investment is stronger the higher the volatility of the underlying quality process.

As the size of the liquidity shock associated with more incumbent innovation investment is a function of project scale, the reduction in innovation investment brings down the underlying volatility of the quality process, $d\sigma(z)/d\lambda < 0$. This dampens the initial rise in the risk premium caused by the increase in market risk aversion. The total effect on the risk premium is given by:

$$\frac{d\left[\lambda\sigma(z)^2\right]}{d\kappa} = \left[\underbrace{\sigma(z)^2}_{\substack{\text{direct effect} \\ \text{(risk aversion)}}} + \underbrace{2\lambda\sigma(z)\sigma'(z)\frac{dz}{d\lambda}}_{\substack{\text{indirect effect} \\ \text{(innovation investment)}}} \right] \cdot \frac{d\lambda}{d\kappa}. \tag{5.27}$$

Under the functional form assumption from above, the comparative statics on the risk premium boil down to:

Proposition 2 (Risk premium)**.** *Assume that parameters are such that* $1 > \underline{\sigma}\lambda$*. Under Assumption 1, the comparative statics on the market risk premium component related to incumbent firms' investment are given by:*

$$\frac{d\left[\lambda\sigma(z)^2\right]}{d\kappa} = \frac{\underline{\sigma} z}{\eta-1}\left[\frac{\eta(1-\underline{\sigma}\lambda)-1}{(1-\underline{\sigma}\lambda)}\right]\frac{d\lambda}{d\kappa}. \tag{5.28}$$

Proof. Appendix A.8.2. □

When the cost function of R&D is sufficiently convex, that is, when η is large and $\eta(1-\underline{\sigma}\lambda)-1>0$, an increase in investor effective risk aversion raises the market risk premium. However, the market risk premium can decline when investors' effective risk aversion rises, but only when market risk aversion is already very high, such that $\eta(1-\underline{\sigma}\lambda)$ is small. This is the case when the fraction of liability-driven investors β in the market is large. The intuition is as follows: When the share of liability-driven investors is high, changes in the regulatory tightness parameter κ have a strong impact on the market risk premium. In fact, the strength of this effect is convex in β. As effective risk aversion rises, movements in the risk premium become more important for firms' investment decisions relative to their resource cost (as captured by ζz^η). Consequently, when λ is high, the risk premium becomes the constraining factor on innovation. Any further increase in λ, for instance via κ, may then lead firms to cut back on innovation more than one-to-one to avoid the convex premium effect. Corollary 1 summarises this result.

Corollary 1 (Investor composition and risk premium)**.** *Assume that parameters are such that $(\eta - 1)(1 - \beta) > \eta\underline{\sigma}\gamma$. Then, the risk premium component capturing incumbent investment, $\lambda\sigma(z)^2$ is increasing in the tightness of the regulatory constraint κ.*

Proof. The log-derivative is $d\ln\left[\lambda\sigma(z)^2\right]/d\ln(\lambda) = 1 + d\ln(\sigma(z))/d\ln(z) \cdot d\ln(z)/d\ln\lambda$. Use $\sigma(z) = \sqrt{\underline{\sigma}z}$ to get $d\ln\left[\lambda\sigma(z)^2\right]/d\ln\lambda = \left[(\eta-1) - \eta\lambda\underline{\sigma}\right]/\left[(\eta-1)(1-\lambda\underline{\sigma})\right]$. Its sign depends on $(\eta - 1) - \eta\lambda\underline{\sigma} > 0$. Finally, $\lambda = \gamma(2\kappa + \gamma)/[2\kappa(1-\beta) + \gamma]$ and re-arranging yields the result. □

Entry effect. In general equilibrium tightening the regulatory constraint κ affects innovation by outsiders through three channels. First, in response to a higher risk premium, incumbent firms scale back their investment as described above. This reduces their demand for labour and therefore the equilibrium wage, reallocating resources towards production and outsiders. This standard *reallocation effect* can be found in most endogenous growth models (Aghion et al., 2014).

Second, a higher risk premium on incumbent investment lowers their stock prices on impact, thus decreasing the expected value of being an incumbent firm in the first place. This negative *risk premium effect* discourages entry and counteracts the positive reallocation effect.

Third, both the risk premium effect and the reallocation effect are amplified in *general equilibrium effects*. Because the risk premium on incumbent firms' stocks (5.23) depends not only on incumbent investment but also on creative destruction risk, any increase in entry feeds back into the risk premium for incumbents. When entry rates increase, this general equilibrium feedback further reduces incumbent innovation and boosts reallocation while simultaneously lowering the value of entry. Differentiating z^e in (5.21) illustrates the three effects:

$$\frac{dz^e}{d\kappa} = -\frac{1}{\Xi}\left[\underbrace{\frac{d\left[(2-\vartheta)\phi(z)z\eta^{-1} - z\right]}{d\lambda}}_{\text{Reallocation effect}} + \underbrace{\frac{d\left[\lambda\sigma(z)^2\right]}{d\lambda}}_{\text{RP effect}} + \underbrace{z^e\frac{d\Xi}{d\lambda}}_{\text{GE effect}}\right] \cdot \frac{d\lambda}{d\kappa}. \tag{5.29}$$

For general functional forms for $\sigma(z)$, the direction of the net entry effect depends on parameter values and how quickly volatility of the liquidity shocks rises as firms increase investment. Since both the risk premium effect and the general equilibrium effect are negative, the reallocation effect must be strong enough for the entry response to be positive. In other words, the rise in the risk premium must depress incumbent investment more than it discourages entry, so that enough labour is freed up and the cost of entry innovation falls sufficiently to compensate outsiders for the lower value of entry (along with any additional general equilibrium effects).

With the functional form assumption on $\sigma(z)$ used above, the net effect on outside innovators can be summarised as follows:

Proposition 3 (Entry effect)**.** *The net effect of a tighter regulatory constraint κ on liability-driven investors on entry innovation is:*

$$\frac{dz^e}{d\kappa} = \left[\frac{(2-\eta-\vartheta)kz - (\eta-1)\underline{z}^e}{(\eta-1)\Xi^2}\right]\frac{d\lambda}{d\kappa}, \tag{5.30}$$

where $k \equiv (\underline{\sigma}[(1-\vartheta)\nu+1]+1)/\eta$. The effect is positive if $(2-\eta-\vartheta)kz > (\eta-1)\left[\frac{(1-\vartheta)\nu L}{\psi} - r\right] > 0$.

Proof. Appendix A.8.2. □

As with the effect on the risk premium, Proposition 3 implies that the size of the reallocation effect and therefore the sign of the entry response depends on market risk aversion, and thus on investor composition. When market risk aversion is high, the risk premium effect on entry becomes stronger. At the same time, the reallocation effect weakens because incumbents become less responsive to changes in the risk premium.[20] Corollary 2 summarises the parameter condition under which the net entry effect is positive.

Corollary 2 (Investor composition and entry)**.** *Assume that parameters satisfy the requirements of Proposition 3. Then, the reallocation effect dominates the risk premium and general equilibrium effects, and the entry response is positive if*

$$\lambda < \frac{1}{\underline{\sigma}} - \left[\frac{(\eta-1)\underline{z}^e}{(2-\vartheta-\eta)k}\right]^{\eta-1}\frac{\zeta\nu\eta}{\psi\underline{\sigma}}. \tag{5.31}$$

Proof. Solve (5.30) for z and use $z = [(1-\underline{\sigma}\lambda)\psi/(\zeta\eta\nu)]^{1/(\eta-1)}$. □

Aggregate effect. The expected growth rate is a weighted average of incumbent innovation z and entry innovation z^e. A tightening of the regulatory constraint κ therefore affects

[20] To see this differentiate (5.26) with respect to λ.

growth via same three effects on the risk premium, reallocation between incumbents and outsiders, and general equilibrium amplification. One can distinguish two cases.

When the reallocation effect is weak, entry rates and incumbent innovation are decreasing in κ, and so is growth. When the reallocation effect is sufficiently strong, however, entry rates are increasing in κ. In this case, more innovation by outsiders can compensate for lower incumbent investment and the relationship between κ and the growth rate is hump-shaped. For low degrees of regulation, the growth rate is increasing in the tightness of the regulatory constraint on liability-driven investors. When the constraint becomes *too tight*, growth falls.

As a consequence, there must also be a growth-maximising level of regulation κ^* that balances the positive entry response against lower incumbent innovation. Proposition 4 and Corollary 3 contain the formal proofs.

Proposition 4 (Growth effect)**.** *Assume parameters satisfy the condition* $(2-\eta-\vartheta)kz < (\eta-1)\left[(1-\vartheta)\nu L/\psi - r\right]$*, such that the reallocation effect is not sufficiently strong to offset the risk premium effect. Then, the growth rate is decreasing in the tightness of the regulatory constraint* κ*.*

Proof. Follows directly from Proposition 3 and (5.26). □

Corollary 3 (Growth-maximising regulation)**.** *Assume that parameters satisfy* $(2-\eta-\vartheta)kz > (\eta-1)\left[(1-\vartheta)\nu L/\psi - r\right]$*, such that the reallocation effect is sufficiently strong. Then, there exists a hump-shaped relationship between the tightness of the regulatory constraint* κ *and economic growth, and a growth-maximising level of regulation* κ^**.*

Proof. Appendix A.8.2. □

5.4 Discussion

Before moving to the quantitative model, I briefly want to discuss the key assumptions in the model and how to interpret the role of pension funds in this context.

The hump-shape and its drivers. As Propositions 3 and 4 illustrate, from a theory perspective the net effect of a change in market risk aversion, such as the pension fund reform studied in the empirical part of the paper, on economic growth is not necessarily negative. In particular, to the extent that tighter constraints on equity investment allow for reallocation of resources between firms, any negative impact on the innovation rate of affected firms may be dampened or even overturned in general equilibrium.[21] This mechanism is driven by two fundamental assumptions.

First, in the model, reallocation can lead to an increase in growth because there is a gap in innovation impact between incumbents and outsiders. Outsider innovation boosts product quality by a net step size $\nu - 1$, while incumbent innovation advances product quality only incrementally. When incumbents and outsiders are equally effective, an increase in the risk premium driven by tighter regulation on investors always reduces growth. The empirical evidence suggests that entry innovation indeed tends to be more radical than incumbent innovation (Akcigit and Kerr, 2018). In fact, much of the discussion about the role of financing, and in particular venture capital, rests on the insight that innovation by outsiders is an important dimension of radical technical change (Akcigit et al., 2022a).

Second, the entry response in the model is only positive because the tightening in regulation on liability-driven investors disproportionately affects the cost of capital for incumbent firms. In the baseline model, I focus on the case when outside innovation is only financed by inside equity, while incumbent investment depends on equity markets. This assumption broadly reflects the fact that smaller firms receive relatively less capital from larger institutional investors such as pension funds (Robb and Robinson, 2014). In a model in which outside innovators received the same fraction of their financing from pension funds and also shared the same risk profile, the increase in the risk premium due to regulatory tightening would equally reduce incumbent and outsider innovation. Any model extension in which outsiders are funded in stock markets would strengthen the negative effect on growth coming from tighter regulation. When outsider innovation is riskier than incumbent innovation, a rise in effective risk aversion would still lower growth, and the reallocation channel would need to be particularly strong to generate a positive entry response.[22]

Inside versus outside innovation. One may wonder about the distinction between incumbents and outsiders in the context of the model. In the standard Schumpeterian growth framework, entrants are typically interpreted as small start-ups or entrepreneurial innovators who invest in innovation to unseat larger incumbents. An alternative interpretation in the context of my model is of incumbents as large public companies who make up the market index and of outsiders as the segment of firms just below that. This interpretation is

[21] This trade-off also distinguishes the Schumpeterian framework from Romer (1990) or other AK-type endogenous growth models, in which higher risk premia unambiguously reduce the quantity and quality of innovation.

[22] Some innovative firms receive funding from venture capital backed by pension funds. Kortum and Lerner (2000) and Gompers and Lerner (2001) argue that the increase of pension investment was instrumental in the development of the U.S. venture capital sector.

convenient because a large fraction of institutional investment tends to be concentrated in those large indices that serve as their investment benchmark. As such the reallocation channel uncovered in the model could be thought of as a reallocation not between incumbents and market entrants, but between larger public and smaller private firms.

The model therefore also yields additional predictions on the impact of regulation on *market concentration*. One interpretation of incumbent firms in the baseline model is that of large, listed firms. Although there has recently been a move towards private markets, pension funds and other institutional investors invest primarily in these large public firms. Entrant firms in the model can be interpreted as outside innovators, who are not necessarily small, but who have higher cost of capital, for example because they do not form part of an investment index. Any policy change that affects liability-driven investors' demand for equities changes the cost of capital for incumbents and, through their investment policies, factor prices in secondary markets, which crowds out entry. In the model, crowding out happens through the labour market but it could well be other markets with inelastic supply of factor inputs, for instance machines or skilled labour.

The model therefore links institutional investment, market concentration, and growth, and could be used in future work to provide a financial explanation for the rise of superstar firms (Autor et al., 2020). See for instance Jiang et al. (2025) for such a finance-driven theory linking passive investment and market concentration. In the Appendix, I extend the model to allow for heterogeneous firms and show that a decrease in liability-driven investors' equity demand decreases market concentration and reduces the average firm size.

6 Quantifying the impact on economic growth

In this section, I quantify the growth impact of pension investment using the empirical estimates from the natural experiment and the theoretical model from the previous section. I then simulate the reform via a tightening of liability-driven investors' risk-bearing constraint. Finally, I decompose the macro effect into its various channels.

6.1 Calibration

I calibrate the model at annual frequency. The model features 11 structural parameters. I identify these parameters using a mixture of calibration and indirect inference with simulated method of moments (SMM). Table 6.1 contains an overview. For the calibration, I split the data in three periods, a pre-reform period from 1985 to 2002, a reform period from 2002 to 2007, and a post-reform period from 2007 onwards. For time series moments, the

Table 6.1: Calibrated parameters.

#	Parameter	Description	Identification	Value
1	L	Labour	Normalisation	1.00
2	κ	Value-at-risk constraint	Normalisation	1.00
3	η	R&D curvature	External	1.75
4	β	Liability-driven share	External	0.25
5	γ	Investor risk aversion	External	1.33
6	r	Discount rate	External	0.05
7	ϑ	Elasticity of substitution	External	0.60
8	$\underline{\sigma}$	Volatility shifter	Internal	0.55
9	ν	Step size outsiders	Internal	1.61
10	ψ	Entry cost	Internal	3.56
11	ζ	R&D cost shifter	Internal	1.25

baseline for my calibration is the pre-reform period, while for cross-sectional moments it is the financial year 2001-2002, the last before the announcement.[23]

The quantitative model also requires a functional form for the volatility $\sigma(z_{it})$. To ensure enough quantitative flexibility, I use the power function:

$$\sigma(z_{it}) = z_{it}^{\underline{\sigma}}. \tag{6.1}$$

Normalisations. I normalise household labour supply to $L = 1$. All aggregate variables in the model can therefore be interpreted as per-capita values. The parameter κ captures the tightness of the regulatory constraint on liability-driven investors. As the parameter is only identified relative to γ, I normalise its initial level at $\kappa = 1$. An isomorphic representation of the model would be to normalise the pre-reform level at $\kappa = 0$ and allow for different levels of risk aversion γ^M and γ^L for market-driven and liability-driven investors.[24]

[23] For the entirety of the quantitative section, I have removed the financial crisis when calculating time-series moments. I discuss an alternative calibration in the Appendix.

[24] Setting $\kappa = 0$ and keeping γ the same for both types of investors would imply symmetric portfolio shares for both investors and $\alpha = 1$. Investors would then hold β and $1 - \beta$ shares of the market.

Table 6.2: Targeted moments.

#	Moment	Model	Data	Method	Weight
1	Real interest rate	0.05	0.05	External	n/a
2	Labour income share	0.60	0.60	External	n/a
3	Share of DB pension fund stock holdings	0.12	0.12	External	n/a
4	U.K. equity portfolio share	0.47	0.47	External	n/a
5	Growth rate	0.028	0.028	Internal	1.00
6	Entry rate	0.041	0.035	Internal	1.00
7	R&D elasticity	1.200	1.200	Internal	1.00
8	Equity risk premium	0.067	0.045	Internal	1.00

External calibration. First, the parameters η and ϑ are standard features of innovation models. ϑ is the Cobb-Douglas weight on labour in the production function and hence the labour share of income. Typical estimates put $\vartheta = 0.6$. The parameter η governs the curvature of the R&D cost function for incumbent firms. The growth literature typically uses a value between 2 and 3. Akcigit and Kerr (2018) use 2.5, but there is evidence that a value closer to 1.5 is appropriate for larger firms (Dechezleprêtre et al., 2023). As a baseline quantification, I set $\eta = 1.75$.

Second, the parameters r and β are readily observable in the data. Because of linear utility (5.1), the household's discount rate r is the equilibrium interest rate in the model. The average real interest rate in the U.K. for the period from 1985 to 2002 is around 5 percent. Following the empirical results in the paper, I interpret *liability-driven investors* to refer to *defined-benefit pension funds*.

The Office of National Statistics (ONS) collects data on the aggregate shareholding in listed British companies by shareholder type. For the pre-reform period, the average fraction of U.K. shares held by DB pension schemes is 12 percent. In the model, this fraction is symmetric across stocks and given by $\beta X_t^L/[(1-\beta)X_t^L + \beta X_t^M] == \beta\alpha^L W_t^L/Q_t$, see (5.20). Given an equity portfolio share of 47 percent in the initial steady state, this implies $\beta = 0.12/0.47 \approx 0.25$. In equilibrium, the portfolio share is given by (5.13), but using the risk premium (5.23) the portfolio share collapses to the fully parametric expression. I back out $\gamma = 1.33$ which supports the observed asset allocation.

Internal calibration. The remaining four parameters $\Gamma = \{\underline{\sigma}, \nu, \psi, \zeta\}$ are calibrated to jointly reproduce five moments based on U.K. macro data and my empirical results in Section 4. I use a Simulated Method of Moments (SMM) approach, following the methodology in our paper on firm dynamics with financial friction (Aghion, Bergeaud, Dewatripont and Matt, 2025). Specifically, the procedure involves searching over the parameter space $\Gamma \in \boldsymbol{h}(\Gamma)$ to minimise the distance between model generated moments $\boldsymbol{\mathcal{M}}(\Gamma)$ and their empirical counterparts $\boldsymbol{\mathcal{M}}_0$. The objective function is:

$$\min_{\Gamma \in \boldsymbol{h}(\Gamma)} ||\boldsymbol{W}\left(\boldsymbol{\mathcal{M}}\left(\Gamma\right) - \boldsymbol{\mathcal{M}}_0\right)||_p, \tag{6.2}$$

where $\boldsymbol{W}$ is a weighting matrix, $||\cdot||_p$ denotes the p^{th} norm, and $\boldsymbol{h}(\Gamma)$ is the admissible parameter space. In the baseline calibration, I set weights $[1, 1, 1, 1]$ across moments and use the Euclidean norm ($p = 2$).[25]

The targets are chosen as follows: First, I target the average annual growth rate of the economy in the pre-pension reform period. I choose January 1985 as the start and December 2002 as the end date. Using a conventional Hodrick-Prescott filter, the average annualised growth rate is 2.80 percent.

Second, in general equilibrium, the effects of any firm-level policy propagates via the labour market (5.19) to output and firm entry. To scale the importance of entry innovation for growth, I target an entry rate of 4.5 percent per year. This implicitly also pins down the size of the final good sector.

The results in Section 4.2 provide an estimate for the firm-level response of R&D investment to a change in the share of firm equity held by defined-benefit pension funds. The point estimate for the steady-state-to-steady-state *semi-elasticity of R&D spending* over total assets with respect to a one percentage point decrease in equity holdings is 1.2. The model counterpart is $\zeta z_{it}^{\eta}(q_{it}/Q_t)w_t$. As there is no real notion of assets in the model, I divide this expression by q_{it} to proxy for firm size. I capture the effect of the pension reform via a change in the parameter κ, the tightness of the regulatory constraint. In the model, the semi-elasticity thus is:

$$\varepsilon \equiv -\frac{1}{N}\sum_{i=1}^{I} \frac{d\ln\left(\frac{\zeta z_{it}^{\eta} w_t}{Q_t}\right)}{d\kappa}. \tag{6.3}$$

With $dz/d\lambda$ in (5.26) and the functional form (6.1), the expression becomes $\varepsilon = \eta D/[2\underline{\sigma} -$

[25] The optimisation routine is based on a generalised pattern search algorithm, which is generally more robust than gradient-based methods when calibrating endogenous growth models with a high degree of linearity.

$1 + (\eta - 1)\delta_{it}]d\kappa/d\lambda$, where $\delta_{it} \equiv z_{it}^{2\underline{\sigma}-1}/(2\underline{\sigma}\lambda) - 1$ and $D = d\lambda/d\kappa$. See Appendix D.1 for the derivation. Note that this approach implies that only the firm-level response to a change in the parameter κ is targeted, but that the aggregate elasticity of the growth rate remains untargeted.

Finally, I match the average equity risk premium on U.K. equities for the period between 1985 and 2001, which is 4.41 percent (Damodaran, 2019, p.38). Table 6.2 contains a list of targeted moments in the model and the data. Further notes on the calibration are in Appendix D.1, including untargeted moments and sensitivity analysis.

6.2 Calibrated equilibrium

Untargeted moments. To provide a sense of the model's quantitative fit, I report a series of untargeted moments. The model-implied average annual return on firms' stock μ is 15.8 precent. The risk premium is approximately 6.7 percent, compared to 4.41 in the data. The implied market volatility is 20.7 percent per year, or 5.96 percent per month. Damodaran (2019, p.38) reports an annual volatility of 20.03 percent (5.78 percent per month) for the period between 1981-2001.

Labour used in the production of the final good is $L^P = 0.85$, which implies that around 15 percent of workers are employed in the research sector. Total research spending is defined as $\sum_{i=1}^{N} [\psi z_{it}^e + \zeta z_{it}^\eta] \varphi_{it} w_t / Y_t$ and accounts for 20 percent of GDP, which is much larger than in the data but not surprising given that the model is a Schumpeterian growth model that abstracts from capital accumulation. Finally, at the firm level, the model implies a price earnings ratio of $P_t q_{it}/(\pi_t q_{it} - \zeta z^\eta w_t \varphi_{it})$ of approximately 10.4, which is at the lower end of estimates for the U.K. in the late 1990s and early 2000s.

The aggregate effects of regulation. The key parameter of interest is the tightness of the regulatory constraint κ on the volatility of liability-driven investors' portfolios, which affects growth through investors' risk premium. To illustrate how the key endogenous variables in the model behave as a function of κ, I solve the model for a range of parameter values.

Figure 6.1 shows that a tighter regulatory constraint on liability-driven investors lowers their equity portfolio share. In the pre-reform steady state, approximately 47 percent of their wealth is allocated to equity. To ensure market clearing, market-driven investors short the safe bond. Their portfolio share is larger than one.

As the regulatory constraint tightens, liability-driven investors reduce their stock holdings in incumbent firms. The market risk premium rises to incentivise market-driven investors to buy and clear the market. Consequently, incumbent innovation falls. Although

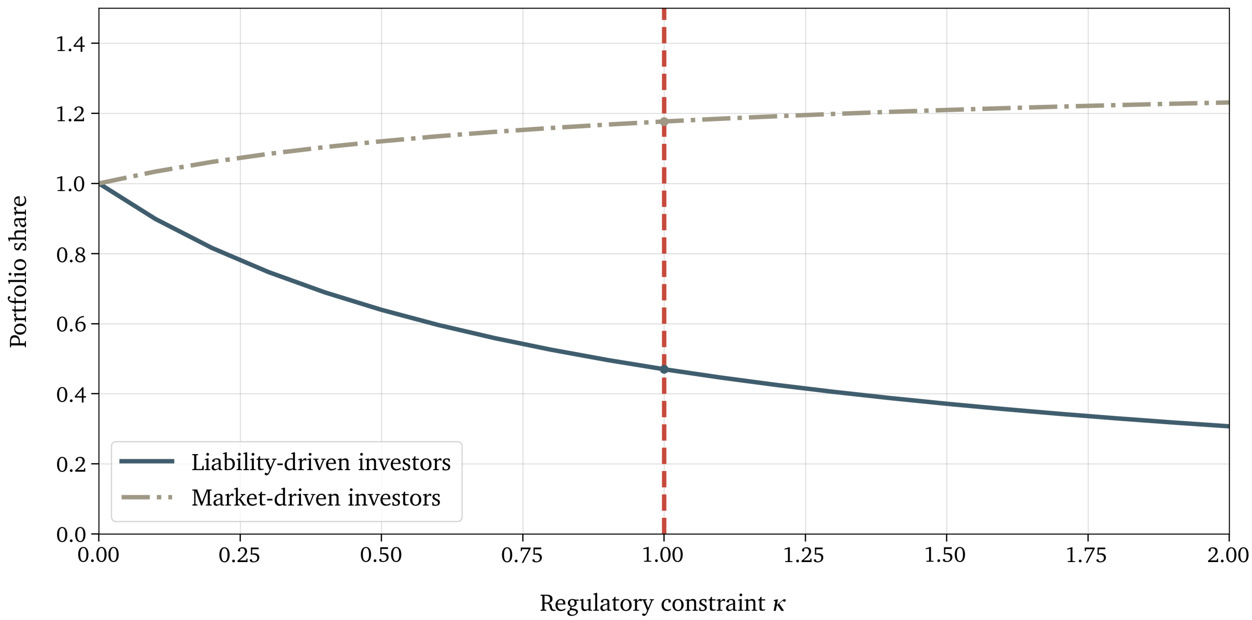

Figure 6.1: Equilibrium portfolio shares.

The figure shows the equilibrium portfolio shares for liability-driven and market-driven investors as a function of the regulatory constraint parameter κ. The red line denotes the calibrated pre-reform steady state.

lower investment rates imply lower volatility in firms' quality level, this feedback channel between investment and the risk premium is not sufficiently strong to compensate for the fall in investor demand due to the tighter regulatory constraint.

While the sign on incumbent innovation is clearly determined in theory, the entry effect is ambiguous. Although lower incumbent innovation frees up resources that can be used for entry lowering the wage and therefore the cost of market entry, a higher risk premium can also reduce the value of becoming an incumbent firm in the first place. This second indirect effect dominates the (positive) reallocation effect in the quantitative model. The net effect on entry is negative. The model therefore predicts that a reduction in the demand for incumbent firms' equity has a net negative effect on firm creation. The joint response then determine the effect on economic growth, as illustrated in Figure 6.2.

6.3 The growth effects of pension fund regulation

Approach. In the final part of the paper, I quantify the growth impact of the Pensions Act 2004. The spirit of this exercise is similar to Aghion et al. (2025). Specifically, holding constant all other model parameters, I vary the tightness of the regulatory constraint κ to match the observed decline in the equity portfolio share for defined-benefit pension funds

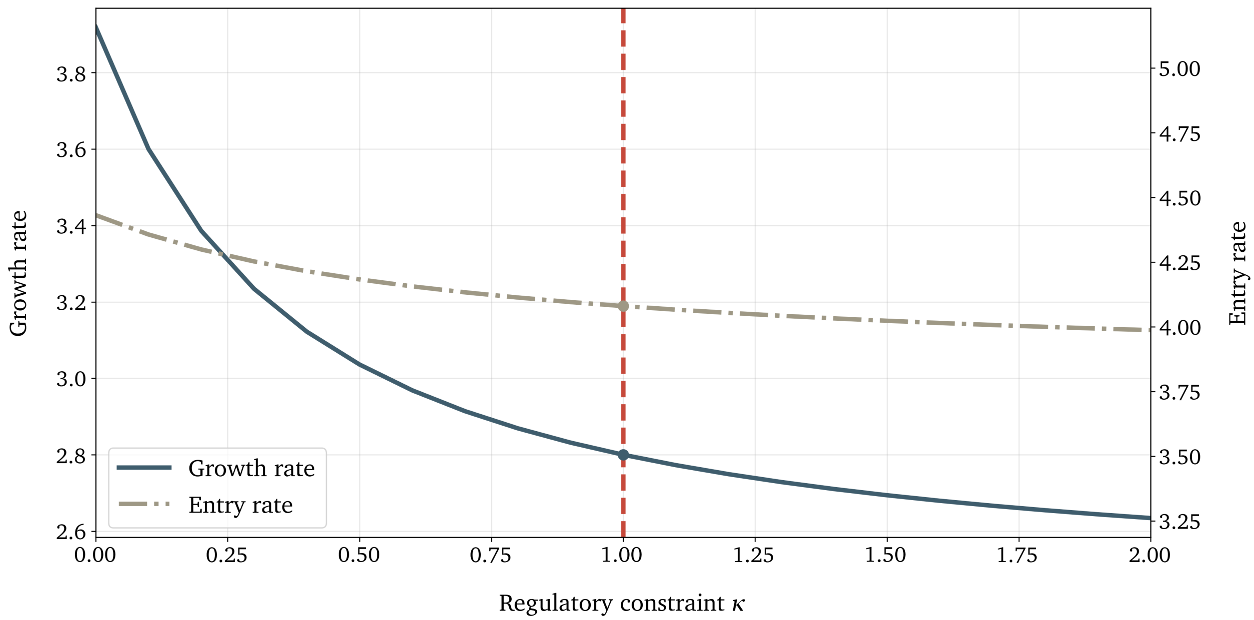

Figure 6.2: Equilibrium growth and innovation.

This figure shows entry innovation (dashed line, right axis) and growth (solid line, left axis) as function of the regulatory constraint parameter κ. The red line denotes the calibrated pre-reform steady state.

over the period from 2002 to 2007 in my data. As the model does not feature transition dynamics, I interpret every year as a new steady state. I then evaluate how much of the decline in the growth rate over that period the model can explain and decompose the relative contributions of incumbent and entry innovation.

Simulation. Given a sequence of pension fund equity portfolio shares observed in the data, $\boldsymbol{\alpha}$, I invert the first-order condition (5.13) to back out a vector of implied regulatory tightness $\boldsymbol{\kappa}$ that rationalises these portfolio shares. Given that the model features aggregate risk, I run a *Monte-Carlo simulation* of 100 firms with 10,000 draws for each steady state. Figure 6.3 shows the implied average path of the growth rate. The model predicts a decline in the annual expected growth rate from 2.80 percent, the pre-reform mean for the period from 1985 to 2002, to 2.66 percent, that is, a reduction of 0.14 percentage points.

Decompositions. The simulation predicts a fall in incumbent innovation rates by about 13 percent from 2.7 percent to 2.35 per year. Similarly, entry rates fall by around 1.8 percent to 3.68 percent per year. At the same time, reduced labour demand from the research sector has a one-off positive effect on output. This effect, however, is tiny at 0.2 percent. Overall, most of the decline in growth rates is driven by a contraction in incumbent innovation with a

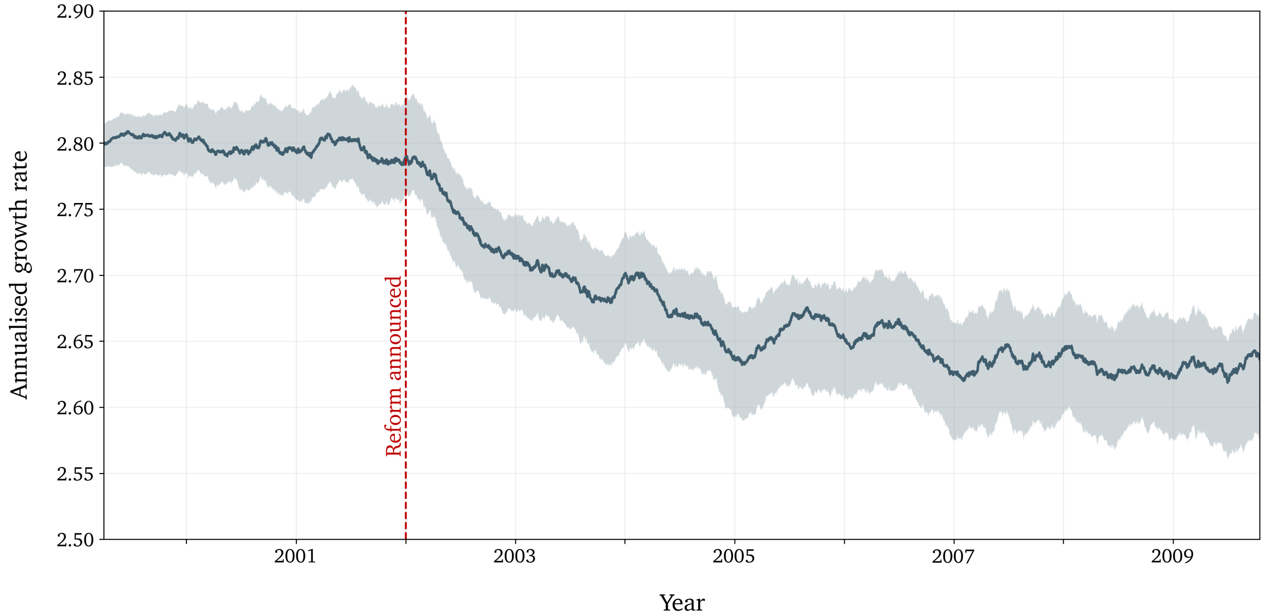

Figure 6.3: Simulated growth path.
The figure shows the simulated growth rate of 10,000 Monte Carlo simulation over 100 firms. The vertical line corresponds to the announcement of the pensions reform. Shaded areas represent confidence bands within one standard deviation of the mean.

small negative effect through lower firm entry. As firms' innovation choices are independent of their quality levels, macro aggregates do not depend on the firm size distribution and the growth rate is unaffected by compositional changes in firm size.

6.4 Extensions

In the Appendix, I extend the model in two key directions. Appendix B introduces aggregate risk across firms. Appendix C extends the model to allow for heterogeneity among firms, and therefore an effect of the firm size distribution on aggregate variables.

7 Conclusion

Since the Global Financial Crisis, many developed economies have seen a slowdown in economic growth and a rise in financial regulation. A popular argument, which is echoed, for instance, in Mario Draghi's recent report on *The Future of European Competitiveness* (Draghi, 2024), is that regulation has limited investors' effective willingness to take risk and thus reduced the amount of capital available for investment in high-risk, high-reward innovation projects.

This paper analyses how financial regulation that limits investors' willingness to take risk affects economic growth. I study a particular example of such a reform, the Pensions Act 2004, which tightened risk requirements on British pension funds and led to a large-scale divestment from equity markets. I show that this reduction in pension fund participation in equity markets reduced valuations for firms more reliant on pension investors before the reform. In response, firms cut back on their long-term investment.

These results suggest that shifts in investor demand can have significant effects on firms' investment choices. I interpret these results as evidence that market segmentation and hence the capitalisation and ability of equity investors to absorb risk is an important determinant of real outcomes. Motivated by these findings, I develop a theory of segmented equity markets and endogenous growth. Firms maximise their stock market valuation and therefore consider how risky investment choices feed back into valuations via risk premia. When the marginal investor becomes more risk averse, risk premia have to rise to clear the market. Firms react to that by cutting back on high-risk investment.

In the final part of the paper, I calibrate the model to my empirical estimates. The calibrated model suggests that the growth impact of the particular reform has been sizeable. A total decline in pension fund equity investment equivalent to 3 percent of market capitalisation results in a 0.14 percentage point drop in annual growth.

A future version of this paper will extend the results in several directions, most importantly it will contain a quantification of the extended model with heterogeneous firms outlined in Appendix C that allows for differences between incumbents based on their firm-specific risk profiles and their loading on aggregate market risk.

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Supplementary Appendix

The Impact of Pension Investment on Economic Growth

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This version: 29th October 2025

Contents

A Appendix – Baseline Model

A.1 Household

The household holds bonds A_t, supplies L units of labour at wage w_t, earns V_t from investors and consumes dC_t. The household maximises (5.1) subject to the budget constraint $dA_t = rA_t dt + w_t L dt + V_t dt - dC_t$. Because utility is linear, the bond market clears at the discount rate r.

A.2 Production

Final good. The competitive final good producer maximises (5.2) subject to $Y = w_t L_t^P + \sum_{i=1}^N \varrho(q_{it}) y_{it}$ by choosing labour L_t^P and intermediate inputs $\{y_{it}\}_{i=1}^N$. w_t is the wage and $\{\varrho(q_{it})\}_{i=1}^N$ are the prices of the available inputs of quality $\{q_{it}\}_{i=1}^N$. The solution is (5.3).

Intermediate goods. Intermediate firms take the demand function (5.3) for their inputs as given. Marginal cost are $1-\vartheta$ units of the final good. Firms choose prices $\varrho(q_{it})$ to solve:

$$\max\Big\{\varrho(q_{it})y_{it} - (1-\vartheta)y_{it}\Big\} \qquad \text{s.t.} \qquad y_{it} = \varrho(q_{it})^{-\frac{1}{\vartheta}} q_{it} L_t^P. \tag{A.1}$$

The first-order condition with respect to the price for a given quality can be written as $(1-1/\vartheta)\,\varrho(q_{it})^{-1/\vartheta} q_{it} L_t^P - (1-\vartheta)/\vartheta\, \varrho(q_{it})^{-1/\vartheta-1} q_{it} L^P = 0$ or equivalently $\varrho(q_{it}) = 1$. Substituting back into (A.1) yields

$$\varrho(q_{it}) = 1, \qquad y_{it} = L_t^P q_{it}, \qquad \text{and} \qquad \pi(q_{it}) = \vartheta L_t^P q_{it}. \tag{A.2}$$

Aggregation. Define aggregate quality Q_t as in (5.4). Substitute $y_{it} = L_t^P q_{it}$ back into (5.2) to get $Y_t = L_t^P Q_t / (1-\vartheta)$. Adding up over firms yields profits $\Pi_t = \vartheta L_t^P \sum_{i=1}^N q_{it} = \vartheta L_t^P Q_t$ and the final good used in production $Y_t^P = (1-\vartheta)\sum_{i=1}^N y_{it} = (1-\vartheta) L_t^P Q_t$. Finally, given labour demand (5.3), the wage is $w_t = \vartheta Q_t/(1-\vartheta)$. We can check the identity $Y_t = Y_t^P + \Pi_t + w_t L_t^P = (1-\vartheta) L_t^P Q_t + \vartheta L_t^P Q_t + \frac{\vartheta}{1-\vartheta} L_t^P Q_t = \frac{1}{1-\vartheta} L_t^P Q_t$. Net output is $Y_t - Y_t^P = \vartheta(2-\vartheta)/(1-\vartheta) L_t^P Q_t$.

A.3 Portfolio choice

A.3.1 Market-driven investors' portfolio choice

Market-driven investors solve (5.9). Note that the law of motion for instantaneous changes in wealth (5.8) has two sources of shocks, stock price volatility $d\mathcal{Z}_{it} \sim \mathcal{N}(0, dt)$ and creative destruction jumps $d\mathcal{J}_{it} \sim Poisson(z^e_{it})$. The expected value of the process is given by $\mathrm{E}\left[dW^M_t\right] = \mathrm{E}\Big[rW^M_t dt + \sum_{i=1}^N \alpha^M_{it}\left(\mu_{it} - r\right)W^M_t dt + \sum_{i=1}^N \alpha^M_{it}\varsigma_{it}W^M_t d\mathcal{Z}_{it} - \sum_{i=1}^N \alpha^M_{it}W^M_t d\mathcal{J}_{it}\Big] = rW^M_t dt + \sum_{i=1}^N \alpha^M_{it}\left(\mu_{it} - r - z^e_{it}\right)W^M_t dt$, for which I used that $\mathrm{E}\left[d\mathcal{Z}_{it}\right] = 0$ and $\mathrm{E}\left[d\mathcal{J}_{it}\right] = z^e_{it}dt$.

Similarly, for the variance we have $\mathrm{Var}\left[dW^M_t\right] = \mathrm{Var}\Big[rW^M_t dt + \sum_{i=1}^N \alpha^M_{it}\left(\mu_{it} - r\right)W^M_t dt + \sum_{i=1}^N \alpha^M_{it}\varsigma_{it}W^M_t d\mathcal{Z}_{it} - \sum_{i=1}^N \alpha^M_{it}W^M_t d\mathcal{J}_{it}\Big] = \sum_{i=1}^N \left(\alpha^M_{it}\right)^2\left(\varsigma^2_{it} + z^e_{it}\right)\left(W^M_t\right)^2 dt$, for which I used that $\mathrm{Var}\left[d\mathcal{Z}_{it}\right] = dt$ and $\mathrm{Var}\left[d\mathcal{J}_{it}\right] = z^e_{it}dt$. With that, the optimisation problem in (5.4) becomes:

$$\max_{\left\{\alpha^M_{it}\right\}_{i=1}^N} \; rW^M_t dt + \sum_{i=1}^N \alpha^M_{it}\left(\mu_{it} - r - z^e_{it}\right)W^M_t dt - \frac{\tilde{\gamma}}{2}\sum_{i=1}^N \left(\alpha^M_{it}\right)^2\left(\varsigma^2_{it} + z^e_{it}\right)\left(W^M_t\right)^2 dt. \tag{A.3}$$

Taking the first-order condition and re-arranging yields (5.10). In equilibrium, the risk premium on stocks is $\mu_{it} - r = (1+\lambda)z^e_{it} + \lambda\varsigma^2_{it}$ via (A.12). Plugging into (5.10) yields a constant demand function $X^M_{it} = \alpha^M_{it}W^M_t$ for all $i = 1, \ldots, N$:

$$X^M = \frac{\lambda}{\tilde{\gamma}}. \tag{A.4}$$

A.3.2 Liability-driven investors' portfolio choice

The same steps as before yield up to a constant $\mathrm{E}\left[dW^L_t\right] = \sum_{i=1}^N \alpha^L_{it}\left(\mu_{it} - r - z^e_{it}\right)W^L_t dt$, and for the variance $\mathrm{Var}\left[dW^L_t\right] = \sum_{i=1}^N \left(\alpha^L_{it}\right)^2\left(\varsigma^2_{it} + z^e_{it}\right)\left(W^L_t\right)^2 dt$. The penalty function is $\mathcal{P}(W^L_t;\kappa) = \mathrm{Var}\left[dW^L_t\right]$. With that, the optimisation problem in (5.4) becomes:

$$\max_{\left\{\alpha^L_{it}\right\}_{i=1}^N} \; \sum_{i=1}^N \alpha^L_{it}\left(\mu_{it} - r - z^e_{it}\right)W^L_t dt - \left(\tilde{\kappa} + \frac{\tilde{\gamma}}{2}\right)\sum_{i=1}^N \left(\alpha^L_{it}\right)^2\left(\varsigma^2_{it} + z^e_{it}\right)\left(W^L_t\right)^2 dt. \tag{A.5}$$

Taking the first-order condition and re-arranging yields (5.13). Using the equilibrium relationship (A.12) yields a constant demand function $X^L_{it} = \alpha^L_{it}W^L_t$ for all $i = 1, \ldots, N$:

$$X^L = \frac{\lambda}{2\tilde{\kappa} + \tilde{\gamma}}. \tag{A.6}$$

A.4 Market clearing conditions

The markets in the economy in the economy are the final good, labour, and bonds, plus N markets for intermediate goods and stocks each. For the first three, we have:

$$Y_t = Y_t^P + dC_t, \tag{A.7}$$

$$L = L_t^P + \sum_{i=1}^{N} \psi z_{it}^e \varphi_{it} + \sum_{i=1}^{N} \zeta z_{it}^\eta \varphi_{it}, \tag{A.8}$$

$$A_t = (1-\beta)\left(1 - \sum_{i=1}^{N} \alpha_{it}^M\right) W_t^M + \beta\left(1 - \sum_{i=1}^{N} \alpha_{it}^L\right) W_t^L, \tag{A.9}$$

and for $i = 1, \ldots, N$ intermediate goods and stocks:

$$y_{it} = \varrho(q_{it})^{-\frac{1}{\vartheta}} L_t^P q_{it}, \tag{A.10}$$

$$Q_t = (1-\beta) X_{it}^M + \beta X_{it}^L. \tag{A.11}$$

A.5 Market price equation

The differential equation for the market price of firm i's stock (5.14) follows from market clearing in the stock market. Starting from (5.20) and substituting the demand functions (5.10) and (5.13), one obtains the expression $(1-\beta)\,(\mu_{it} - r - z_{it}^e)\,/\,[\gamma\,(\varsigma_{it}^2 + z_{it}^e)]\,Q_t + \beta\,(\mu_{it} - r - z_{it}^e)\,/\,[(2\kappa+\gamma)\,(\varsigma_{it}^2 + z_{it}^e)]\,Q_t = Q_t$. Solve for μ_{it} to get (5.23):

$$\mu_{it} = r + (1+\lambda) z_{it}^e + \lambda \varsigma_{it}^2, \tag{A.12}$$

where $\lambda \equiv \gamma(2\kappa+\gamma)/[2\kappa(1-\beta)+\gamma]$ is a parametric expression independent of Q_t. From (5.7) we have $\mu_{it} \equiv \frac{\pi(q_{it}) - \zeta z_{it}^\eta \varphi_{it} w_t}{P(q_{it})} + \frac{P'(q_{it}) z_{it} q_{it}}{P(q_{it})} + \frac{1}{2}\frac{P''(q_{it})[\sigma(z_{it}) q_{it}]^2}{P(q_{it})}$ for the drift, and $\varsigma_{it} \equiv \frac{P'(q_{it})\sigma(z_{it}) q_{it}}{P(q_{it})}$ for the volatility. Using these definitions:

$$\begin{aligned} &\frac{\pi(q_{it}) - \zeta z_{it}^\eta \varphi_{it} w_t}{P(q_{it})} + \frac{P'(q_{it}) z_{it} q_{it}}{P(q_{it})} + \frac{1}{2}\frac{P''(q_{it})\,[\sigma(z_{it}) q_{it}]^2}{P(q_{it})} \\ &\qquad\qquad\qquad = r + (1+\lambda) z_{it}^e + \lambda \left[\frac{P'(q_{it})\sigma(z_{it}) q_{it}}{P(q_{it})}\right]^2. \end{aligned} \tag{A.13}$$

Re-arrange to obtain the price equation (5.14).

A.6 Kolmogorov-forward equation

In equilibrium, all firms choose the same innovation intensity z according to (A.18). Because of that, the distribution of product qualities $p_t(q)$ does not affect aggregate objects such as the growth rate (5.18). For completeness, the evolution of product quality is governed by the Kolmogorov-forward equation (KFE):

$$\frac{\partial p_t(q)}{\partial t} = -\frac{\partial}{\partial q}\left[z_t q_t p_t(q)\right] + \frac{1}{2}\cdot\frac{\partial^2}{\partial q^2}\left[\sigma(z_t)^2 q^2 p_t(q)\right] + z_t^e\left[\frac{1}{\nu}p_t\left(\frac{q}{\nu}\right) - p_t\left(q\right)\right], \tag{A.14}$$

where the first term captures the outflows from quality level q due to successful incremental innovation at intensity z_t; the second terms are movements due to short-run quality fluctuations $\sigma(z_t)$; and the third term represents inflows from quality level q/ν and outflows due to creative destruction at intensity z_t^e.

With z_t being a constant, product quality at any point in time is given by the closed-form expression $q_t = q_0 \exp\left[\left(z - \sigma(z)^2/2\right)t + \sigma(z)\mathcal{Z}_t\right]\nu^{\mathcal{N}_t}$, where $\mathcal{N}_t \sim Poisson\left(z^e t\right)$ and q_0 is the initial quality level on the product line. The distribution of q then follows the mixed Poisson-lognormal distribution:

$$p_t(q) = \sum_{n=0}^{\infty} e^{-\lambda t}\frac{(\lambda t)^n}{n!}\cdot\frac{1}{q\sqrt{2\pi\sigma(z)^2 t}}\cdot e^{-\frac{1}{2\sigma(z)^2 t}\left[\ln(q)-\ln(q_0)-\left(z-\frac{\sigma(z)^2}{2}\right)t-n\ln(\nu)\right]^2}. \tag{A.15}$$

Finally, note that one might be tempted to define a "stationarised" distribution $\tilde{p}_t(\varphi)$ over $\varphi_t \equiv q/Q_t$ by normalising the quality q by the average Q_t. Yet, because the number of firms N is finite, the average Q_t is stochastic and the KFE becomes a mean-field partial differential equation. Since the distribution of product qualities does not affect aggregates in the baseline model, I will defer to the interested reader to the model extensions.

A.7 Equilibrium

A.7.1 General case

Following the standard approach in the literature, I guess that the firm's price function is linear in its quality level $P(q) = Pq$. Moreover, on a balanced growth path all aggregate variables grow at a common constant growth rate, the growth rate of aggregate quality Q. Hence, I define the wage-to-quality ratio $\omega \equiv w/Q$. With that, the stock price equation (5.14) becomes:

$$\left[r + (1+\lambda)z^e\right]P = \max_z\ \pi - \zeta z^\eta \omega + \left[z - \lambda\sigma(z)^2\right]P, \tag{A.16}$$

where $\pi \equiv \vartheta L^P$ as defined in (A.2). As shown in Appendix A.2, the equilibrium wage is simply $\omega = \vartheta/(1-\vartheta)$. General equilibrium in the model is described by three equations in four unknowns $\{L^P, z^e, P\}$. Besides the firm's stock price function (A.16), these equations are the free-entry condition (5.17) and the labour market clearing condition (5.19):

$$L = L^P + \psi z^e + \zeta z^\eta \qquad \text{and} \qquad P = \frac{\psi\omega}{\nu}. \tag{A.17}$$

First, differentiating (A.16) yields an R&D intensity of $z = [\phi(z)P/(\zeta\eta\omega)]^{1/(\eta-1)}$, where I have defined $\phi(z) \equiv 1 - 2\lambda\sigma'(z)\sigma(z)$ to economise on notation. Using the free-entry condition:

$$z = \left[\frac{\phi(z)\psi}{\zeta\eta\nu}\right]^{\frac{1}{\eta-1}}. \tag{A.18}$$

The implicitly defined solution to this equation pins down z as a function of model parameters. Second, substituting z, the free-entry condition, and $\omega = \vartheta/(1-\vartheta)$ into the stock price equation (A.16) yields:

$$\left[r + \lambda\sigma(z)^2 + (1+\lambda)z^e\right]\frac{\vartheta\psi}{(1-\vartheta)\nu} = \vartheta L^P + \frac{\vartheta\psi}{(1-\vartheta)\nu}\left(z - \frac{\zeta\nu}{\psi}z^\eta\right). \tag{A.19}$$

Note that $z - \frac{\zeta\nu}{\psi}z^\eta = \left(1 - \frac{\phi(z)}{\eta}\right)z$. Solve the above for L^P as a function of z^e and get:

$$\frac{L^P}{\psi} = \frac{r + \lambda\sigma(z)^2 + (1+\lambda)z^e + \left(\frac{\phi(z)}{\eta} - 1\right)z}{(1-\vartheta)\nu}. \tag{A.20}$$

Take the labour market clearing condition for the entry rate $L^P/\psi = L/\psi - z^e - (\zeta/\psi)z^\eta$ and substitute in for L^P. Then re-arrange to find the entry rate as a function of model parameters:

$$z^e = \frac{(1-\vartheta)\nu L}{[(1-\vartheta)\nu + 1 + \lambda]\psi} - \frac{r + \lambda\sigma(z)^2}{(1-\vartheta)\nu + 1 + \lambda} - \left[\frac{(2-\vartheta)\frac{\phi(z)}{\eta} - 1}{(1-\vartheta)\nu + 1 + \lambda}\right]z. \tag{A.21}$$

Substitute the entry rate back into (A.20) and re-arrange the expression to obtain labour used in production as a function of model parameters only:

$$L^P = \frac{\psi\left[r + \lambda\sigma(z)^2\right]}{(1-\vartheta)\nu + 1 + \lambda} + \frac{(1+\lambda)L}{(1-\vartheta)\nu + 1 + \lambda} - \psi\left[\frac{1 - \left(\frac{\nu-1-\lambda}{\nu}\right)\frac{\phi(z)}{\eta}}{(1-\vartheta)\nu + 1 + \lambda}\right]z. \tag{A.22}$$

Finally, the expected growth rate in the economy is $g = (\nu - 1)z^e + z$. Using (A.18) and (A.21) the simplified growth rate is:

$$g = \frac{(\nu-1)\left((1-\vartheta)\nu L/\psi - [r + \lambda\sigma(z)^2]\right)}{(1-\vartheta)\nu + 1 + \lambda} + \left(\frac{(2-\vartheta)\nu\left[1 - \left(\frac{\nu-1}{\nu}\right)\frac{\phi(z)}{\eta}\right] + \lambda}{(1-\vartheta)\nu + 1 + \lambda}\right) z. \tag{A.23}$$

To complete the derivation of equilibrium, output $Y = 1/(1-\vartheta)QL^P$ as shown in Appendix A.2.

A.7.2 Simple case

Starting with the HJB equation $[r + (1+\lambda)z^e]P = \max_z \pi - \zeta z^\eta \omega + (z - \lambda\underline{\sigma} z)P$, take the first-order condition to find $z = [(1-\lambda\underline{\sigma})P/(\zeta\eta\omega)]^{1/(\eta-1)}$. Substitute into the HJB and simplify:

$$[r + (1+\lambda)z^e]P = \pi + \frac{\eta-1}{\eta}(1-\lambda\underline{\sigma})P\left[\frac{(1-\lambda\underline{\sigma})P}{\zeta\eta\omega}\right]^{\frac{1}{\eta-1}}. \tag{A.24}$$

Note that the stock price is $P = \psi\omega/\nu$ from the free-entry condition (5.17), the normalised wage is $\omega = \vartheta/(1-\vartheta)$ from (5.3), and profits are $\pi = \vartheta L^P$ from (A.2). Using these expression and solving for L^P yields:

$$L^P = \frac{1}{1-\vartheta}\left(\frac{\psi}{\nu}[r + (1+\lambda)z^e] - \zeta(\eta-1)\left[\frac{(1-\lambda\underline{\sigma})\psi}{\zeta\eta\nu}\right]^{\frac{\eta}{\eta-1}}\right). \tag{A.25}$$

Together with the labour market clearing condition $L = L^P + \psi z^\eta + \zeta z^\eta$, equation (A.25) defines a system of two equations in two unknowns, the entry rate z^e and labour in production L^P. Substituting the latter into the former and solving for the entry rate:

$$z^e = \frac{(1-\vartheta)\nu L/\psi - r}{(1-\vartheta)\nu + 1 + \lambda} - \frac{\zeta\nu(2-\eta-\vartheta)}{\psi[(1-\vartheta)\nu + 1 + \lambda]}\left[\frac{(1-\lambda\underline{\sigma})\psi}{\zeta\eta\nu}\right]^{\frac{\eta}{\eta-1}}. \tag{A.26}$$

Substitute back into (A.25) to obtain labour used in production of the final good:

$$L^P = \frac{(1+\lambda)L + \psi r}{(1-\vartheta)\nu + 1 + \lambda} - \frac{\zeta\left[(\eta-1)\nu + 1 + \lambda\right]}{(1-\vartheta)\nu + 1 + \lambda}\left[\frac{(1-\lambda\underline{\sigma})\psi}{\zeta\eta\nu}\right]^{\frac{\eta}{\eta-1}}. \tag{A.27}$$

The last step is to solve for the growth rate, $g = (\nu - 1)z^e + z$. Substituting (A.26) for z^e and $z = [(1-\lambda\underline{\sigma})P/(\zeta\eta\omega)]^{1/(\eta-1)}$ from and simplify to get:

$$g = (\nu-1)\frac{(1-\vartheta)\nu L/\psi - r}{(1-\vartheta)\nu + 1 + \lambda} + \left[1 + \frac{(\nu-1)(\eta+\vartheta-2)(1-\lambda\underline{\sigma})}{\eta[(1-\vartheta)\nu + 1 + \lambda]}\right] z. \tag{A.28}$$

A.8 Comparative statics

This Appendix contains the derivations for the simple case discussed in Section 5.3 and generalises the results to a more general volatility function $\sigma(z)$.

A.8.1 General case

Regularity condition. I impose the following assumption, which ensures that stock return volatility rises sufficiently smoothly:

Assumption 2. *The volatility $\sigma(z)$ is twice continuously differentiable and (weakly) log-convex in the R&D intensity z.*

Firm-level effect. A tighter constraint κ reduces liability-driven investors' demand for stocks (5.13). On impact, the stock price falls and firms cut back on innovation. Lower investment rates reduce volatility and dampen the effect. The total effect is:

$$\frac{dz}{d\kappa} = \frac{\phi_\lambda(z,\lambda)z}{(\eta-1)\phi(z,\lambda) - \phi_z(z,\lambda)z} \cdot \frac{d\lambda}{d\kappa} < 0, \tag{A.29}$$

where $\phi_\lambda(z,\lambda) = -2\sigma'(z)\sigma(z) < 0$ and $d\lambda/d\kappa = 2\gamma\beta/[2\kappa(1-\beta)+\gamma]^2 > 0$. Log-convexity implies that $\sigma''(z)\sigma(z) + [\sigma'(z)]^2 \geq 0$ such that $\phi_z(z,\lambda) = -2\lambda\left(\sigma''(z)\sigma(z) + [\sigma'(z)]^2\right) \leq 0$ and $dz/d\kappa < 0$.

Risk premium effect. A tightening in investors' regulatory constraint on firm investment raises the risk premium for a given quantity of risk. In response, firms cut back on innovation rates, which lowers the risk premium. The total effect is:

$$\frac{d\left[\lambda\sigma(z)^2\right]}{d\kappa} = \left[\sigma(z)^2 + 2\lambda\sigma(z)\sigma'(z)\frac{dz}{d\lambda}\right]\frac{d\lambda}{d\kappa}. \tag{A.30}$$

Entry effect. As discussed in the main text, the total entry effect consists of a reallocation effect, and risk premium effect and a general equilibrium effect. Differentiating the entry rate with respect to λ yields the expression used in the main text.

Aggregate effect. The growth rate (5.22) inherits these three broad effects from incumbent and entry innovation. When the entry effect is positive, growth is hump-shaped in κ.

A.8.2 Simple case

Risk premium effect. The risk premium component associated with incumbent firms is $\lambda\sigma(z)^2$. Noting that $\sigma(z)^2 = \underline{\sigma} z$ via Assumption 1 and differentiating the expression with respect to λ yields $d[\lambda\sigma(z)^2]/d\lambda = \underline{\sigma} z + \underline{\sigma}(dz/d\lambda)$. Using (5.26) we get (5.28).

Entry effect. Differentiate (5.24) with respect to λ:

$$\frac{dz^e}{d\lambda} = \frac{1}{(\eta-1)\Xi}\left[\frac{(2-\vartheta-\eta)\underline{\sigma} z}{\eta} - z^e\right]. \tag{A.31}$$

Substitute (5.24) and simplify to obtain:

$$\frac{dz^e}{d\lambda} = \frac{1}{\Xi^2}\left[\frac{(2-\vartheta-\eta)\left(\underline{\sigma}\Xi + 1 - \underline{\sigma}\lambda\right) z}{\eta(\eta-1)} - \underline{z}^e\right]. \tag{A.32}$$

Note that $\Xi \equiv (1-\vartheta)\nu + 1 + \lambda$ as defined in Lemma 1. Simplify to obtain (5.30). For the second part of the proposition note that $\underline{z}^e \equiv (1-\vartheta)\nu L/\psi - r$. The result follows.

Aggregate effect. The combined effect on growth is $\frac{dg}{d\lambda} = (\nu-1)\frac{dz^e}{d\lambda} + \frac{dz}{d\lambda}$. Substitute (5.26) and (5.30) to obtain:

$$\frac{dg}{d\lambda} = (\nu-1)\left[\frac{(2-\eta-\vartheta)kz - (\eta-1)\underline{z}^e}{(\eta-1)\Xi^2}\right] - \frac{z}{(\eta-1)(1-\underline{\sigma}\lambda)}. \tag{A.33}$$

When $2-\eta-\vartheta < 0$, the expression is negative. When $2-\eta-\vartheta > 0$, the first part is positive as long as $(2-\eta-\vartheta)kz > (\eta-1)\underline{z}^e$ and $(\nu-1)\left[\frac{(2-\eta-\vartheta)kz-(\eta-1)\underline{z}^e}{\Xi^2}\right] > \frac{z}{(1-\underline{\sigma}\lambda)}$ or equivalently:

$$\underbrace{(\nu-1)\left[(2-\eta-\vartheta)kz - (\eta-1)\underline{z}^e\right]}_{\equiv\mathcal{L}(\lambda)} > \underbrace{\Xi^2\left(1-\underline{\sigma}\lambda\right)^{\frac{2-\eta}{\eta-1}}\left(\frac{\psi}{\zeta\eta\nu}\right)^{\frac{1}{\eta-1}}}_{\equiv\mathcal{R}(\lambda)}, \tag{A.34}$$

where $\Xi \equiv (1-\vartheta)\nu + 1 + \lambda$ as before. The left-hand side of the inequality in (A.34) is decreasing in λ as $dz/d\lambda < 0$ via (5.26). The right-hand side is increasing as:

$$\frac{d\mathcal{R}(\lambda)}{d\lambda} \propto \frac{d\left[\Xi^2\left(1-\underline{\sigma}\lambda\right)^{\frac{2-\eta}{\eta-1}}\right]}{d\lambda} = 2\Xi\left(1-\underline{\sigma}\lambda\right)^{\frac{2-\eta}{\eta-1}} + \Xi^2\left(\frac{2-\eta}{\eta-1}\right)\left(1-\underline{\sigma}\lambda\right)^{\frac{3-2\eta}{\eta-1}} > 0, \tag{A.35}$$

given $2-\eta-\vartheta > 0$. The intermediate value theorem implies that (A.34) has exactly one solution $\lambda^* \in (0, \underline{\sigma}^{-1})$ if (i) $\mathcal{L}(0) > \mathcal{R}(0)$ and (ii) $\mathcal{L}\left(\underline{\sigma}^{-1}\right) < \mathcal{R}\left(\underline{\sigma}^{-1}\right)$.[26] Condition (i) is

[26] Note that for $\lambda \to \underline{\sigma}^{-1}$, we have $z \to 0$.

satisfied if:

$$\left((2-\eta-\vartheta)k-\frac{[(1-\vartheta)\nu+1]^2}{\nu-1}\right)\left(\frac{\psi}{\eta\zeta\nu}\right)^{\frac{1}{\eta-1}}>(\eta-1)\underline{z}^e, \tag{A.36}$$

where $k\equiv(\underline{\sigma}[(1-\vartheta)\nu+1]+1)/\eta$. Condition (ii) holds trivially as $\mathcal{L}\left(\underline{\sigma}^{-1}\right)=-(\nu-1)(\eta-1)\underline{z}^e<0$ and $\mathcal{R}\left(\underline{\sigma}^{-1}\right)=0$. Hence, $g(\lambda)$ is hump-shaped. As λ is monotonically increasing in κ, $g(\kappa)$ is hump-shaped as long as $\lambda(\kappa^*)<\underline{\sigma}^{-1}$, which is the case if $1-\beta>\underline{\sigma}\gamma$.

B Appendix – Extended Model with Aggregate Risk

This Appendix extends the model presented in Section 5 and Appendix A by introducing aggregate risk that affects firms' quality processes. Section B.1 describes the main changes in the extended model setup. Section B.2 presents the model equilibrium.

B.1 Modified environment

B.1.1 Households and production

The structure of the household and production side remains unchanged as described in Sections 5.1.1 and 5.1.2.

B.1.2 Intermediate firms

Innovation. The quality process in (5.5) is subject to an additional aggregate risk factor $d\mathcal{Z}_t^a$, common across all $i = 1, \ldots, N$ product lines. Throughout this Appendix, I denote variables relating to the aggregate risk factor by a superscript a. The aggregate factor is normally distributed with mean zero and standard deviation σ^a. All firms load equally on the aggregate factor. The quality on a product line follows the generalised process:

$$\frac{dq_{it}}{q_{it}} = z_{it}dt + \sigma(z_{it})d\mathcal{Z}_{it} + \sigma^a d\mathcal{Z}_t^a + (\nu - 1)d\mathcal{J}_{it}. \tag{B.1}$$

As before, $d\mathcal{Z}_{it}$ captures idiosyncratic quality shocks and $d\mathcal{J}_{it}$ is the specific creative destruction shock with arrival rate z_{it}^e.

Stock returns. Stock returns depend on firms' quality level via prices. Given the quality process in (B.1), one can postulate a price process $P(q_{it})$. The return on firm i's stock can be written in parallel to (5.6):

$$dR(q_{it}) = \mu_{it}dt + \varsigma_{it}d\mathcal{Z}_{it} + \varsigma_{it}^a d\mathcal{Z}_t^a - d\mathcal{J}_{it}, \tag{B.2}$$

Note that the creative destruction shock pushes the quality on a product line by ν but wipes out the shareholders of the firm that previously operated as the incumbent on that particular line. The short-hand coefficients for the drift and the volatility in equation (B.2) are given by the following set of expressions:

$$
\begin{aligned}
\mu_{it} &\equiv \frac{\pi(q_{it}) - \zeta z_{it}^{\eta}\varphi_{it}w_t}{P(q_{it})} + \frac{P'(q_{it})z_{it}q_{it}}{P(q_{it})} + \frac{1}{2}\frac{P''(q_{it})\left[\sigma(z_{it})^2 + (\sigma^a)^2\right]q_{it}^2}{P(q_{it})} \\
\varsigma_{it} &\equiv \frac{P'(q_{it})\sigma(z_{it})q_{it}}{P(q_{it})} \\
\varsigma_{it}^a &\equiv \frac{P'(q_{it})\sigma^a q_{it}}{P(q_{it})}.
\end{aligned}
\tag{B.3}
$$

Here ς_{it}^a is the stock price volatility component for firm i that is driven by the aggregate factor.

B.1.3 Investors

Investors face additional aggregate risk, which is correlated across firms and cannot be diversified. Market-driven investors' wealth evolves according to:

$$
\frac{dW_t}{W_t} = rdt + \sum_{i=1}^{N}\alpha_{it}^M(\mu_{it} - r)\,dt + \sum_{i=1}^{N}\alpha_{it}^M\left(\varsigma_{it}d\mathcal{Z}_{it} + \varsigma_{it}^a d\mathcal{Z}_t^a\right) - \sum_{i=1}^{N}\alpha_{it}^M d\mathcal{J}_{it}. \tag{B.4}
$$

The instantaneous variance of market-driven investors' wealth is given by $\mathrm{Var}\left[dW_t^M/W_t^M\right] = \sum_{i=1}^N\left(\alpha_{it}^M\varsigma_{it}\right)^2dt + \sum_{i=1}^N\left(\alpha_{it}^M\right)^2 z_{it}^e dt + \mathrm{Var}\left[\sum_{i=1}^N\alpha_{it}^M\varsigma_{it}^a dZ_t^a\right]$. Noting that aggregate shocks are perfectly correlated across investors, one can re-write this expression as $\mathrm{Var}\left[dW_t^M/W_t^M\right] = \sum_{i=1}^N\left(\alpha_{it}^M\right)^2\left(\varsigma_{it}^2 + z_{it}^e\right)dt + \sum_{i=1}^N\sum_{j=1}^N\mathrm{Cov}\left(\alpha_{it}^M\varsigma_{it}^a d\mathcal{Z}_t^a, \alpha_{jt}^M\varsigma_{jt}^a d\mathcal{Z}_t^a\right) = \sum_{i=1}^N\left(\alpha_{it}^M\right)^2\left(\varsigma_{it}^2 + z_{it}^e\right)dt + \left[\sum_{i=1}^N\left(\alpha_{it}^M\varsigma_{it}^a\right)^2 + 2\sum_{i<j}\alpha_{it}^M\alpha_{jt}^M\varsigma_{it}^a\varsigma_{jt}^a\right]dt = \sum_{i=1}^N\left(\alpha_{it}^M\right)^2\left(\varsigma_{it}^2 + z_{it}^e\right)dt + \left(\sum_{i=1}^N\alpha_{it}^M\varsigma_{it}^a\right)^2 dt$, where the subscript $i < j$ in the sum operator denotes the sum over all distinct unordered pairs to avoid double counting.

Liability-driven investors' problem translates *mutatis mutandis* to the generalised process (B.2). Investors solve their optimisation problems (5.9) and (5.12) subject to the modified laws of motions for wealth. Their demand functions are given by the following two expressions:

$$
\begin{aligned}
X_{it}^M &= \frac{\mu_{it} - r - z_{it}^e - \gamma\varsigma_{it}^a\left(\sum_{j\neq i}^{N}X_{jt}^M\varsigma_{jt}^a\right)}{\gamma\left[\varsigma_{it}^2 + z_{it}^e + (\varsigma_{it}^a)^2\right]} \\
X_{it}^L &= \frac{\mu_{it} - r - z_{it}^e - (2\kappa+\gamma)\varsigma_{it}^a\left(\sum_{j\neq i}^{N}X_{jt}^L\varsigma_{jt}^a\right)}{(2\kappa+\gamma)\left[\varsigma_{it}^2 + z_{it}^e + (\varsigma_{it}^a)^2\right]}.
\end{aligned}
\tag{B.5}
$$

Compared to the baseline model, the demand function (B.5) features two additional terms: The stock price volatility of the aggregate shock ς^a_{it} and a tilting component $\varsigma^a_{it}\left(\sum_{j\neq i}^{N} X^M_{jt}\varsigma^a_{jt}\right)$, which represents the covariance between stock i and all other stocks in the portfolio scaled by the exposure to the aggregate factor. The larger a firm, and therefore the higher its stock price volatility ς^a_{it} in absolute terms, the higher its marginal contribution to total portfolio risk. Another interpretation of this term is that of a cross-asset externality, capturing the additional exposure to the aggregate factor coming from holding stock i.

B.1.4 Stock price and investment

Firms maximise their stock price. In equilibrium, investor risk aversion gives rise to a risk premium. In the model with aggregate risk, this risk premium is affected by investor tilting across stocks in response of firms' loading on aggregate shocks, which in turn depends on their stock prices via (B.3). Hence, firms stock price equations depend implicitly on investors' entire portfolio allocation across all N stocks. Imposing market clearing in each stock market, $\beta X^L_{it} + (1-\beta)X^M_{it} = 1$, yields

$$\frac{\frac{\mu_{it}-r-z^e_{it}}{\lambda} - \varsigma^a_{it}\left[\beta\sum_{j\neq i}^{N} X^L_{jt}\varsigma^a_{jt} + (1-\beta)\sum_{j\neq i}^{N} X^M_{jt}\varsigma^a_{jt}\right]}{\varsigma^2_{it} + z^e_{it} + (\varsigma^a_{it})^2} = 1, \tag{B.6}$$

where is weighted market risk aversion $\lambda \equiv \gamma(2\kappa+\gamma)/[2\kappa(1-\beta)+\gamma]$ as defined in (5.15). Defining the term in brackets as $\mathcal{B}_{it} \equiv \beta\sum_{j\neq i}^{N} X^L_{jt}\varsigma^a_{jt} + (1-\beta)\sum_{j\neq i}^{N} X^M_{jt}\varsigma^a_{jt}$, one can write (B.6) as:

$$\mu_{it} - r = (1+\lambda)z^e_{it} + \lambda\left[\varsigma^2_{it} + (\varsigma^a_{it})^2\right] + \lambda\varsigma^a_{it}\mathcal{B}_{it}. \tag{B.7}$$

With that, one can recover the firm's Hamilton-Jacobi-Bellman equation from market clearing in the stock market:

$$\max_{z_{it}}\left\{\begin{array}{c} \pi(q_{it}) - \zeta z^\eta_{it}\varphi_{it}w_t + P'(q_{it})z_{it}q_{it} \\ +\frac{1}{2}P''(q_{it})\left[\sigma(z_{it})^2 + (\sigma^a)^2\right]q^2_{it} - \lambda\varsigma^a_{it}\mathcal{B}_{it}P(q_{it}) \\ -\left[r + \lambda\varsigma^2_{it} + \lambda\left(\varsigma^a_{it}\right)^2 + (1+\lambda)z^e_{it}\right]P(q_{it}) \end{array}\right\} = 0. \tag{B.8}$$

Note that the aggregate factor $\mathcal{B}_{it}$ drags down the firm's valuation proportional to market risk aversion. Using the definition of the coefficient ς^a_{it} in equation (B.3), one can rewrite $\lambda\varsigma^a_{it}\mathcal{B}_{it}P(q_{it}) = \lambda\sigma^a\mathcal{B}_{it}P'(q_{it})q_{it}$. It then becomes clear that the exposure to aggregate risk effectively introduces a downward drift in the firm's valuation, the extend of which depends on how much firms quality growth and hence its size adds to the weighted average exposure of investors to the aggregate risk factor, captured by the term $\mathcal{B}_{it}$.

The firm maximises (B.8). As the additional terms related aggregate risk cannot be affected by the firm's choice of drift z_{it}, these terms only enter the first-order condition via the stock value $P(q_{it})$. Formally, the first-order condition is the same as (5.16), but of course the price is the solution to (B.8).

B.1.5 Closing the model

The remainder of the model parallels the baseline case. Free-entry and growth are characterised by (5.17) and (5.18), and the market-clearing conditions (A.7) to (A.11) hold. The Kolmogorov forward equation is:

$$\begin{aligned}\frac{\partial p_t(q)}{\partial t} &= -\frac{\partial}{\partial q}\left[z_t q_t p_t(q)\right] + \frac{1}{2}\cdot\frac{\partial^2}{\partial q^2}\left[\left(\sigma(z_t)^2 + (\sigma^a)^2\right) q^2 p_t(q)\right] \\ &\quad + z_t^e\left[\frac{1}{\nu}p_t\left(\frac{q}{\nu}\right) - p_t\left(q\right)\right].\end{aligned} \tag{B.9}$$

B.2 Equilibrium

We can now discuss the equilibrium in this economy. I will first formally define the growth path and then derive firms' equilibrium innovation.

B.2.1 Equilibrium definition

Definition 2. *The economy is on a stochastic balanced growth path if all aggregate variables – output Y_t, consumption C_t, profits Π_t, wages w_t, and intermediate production costs Y_t^P – grow at a common expected growth rate g_t, the growth rate of aggregate quality Q_t defined in* (5.18)*; the risk-free rate is constant at r, the risk-neutral household's discount rate defined in* (5.1)*; and stock returns follow the process in* (B.2)*. Agents' optimisation problems satisfy the following conditions:*

(i) households choose consumption and savings according to (5.1)*;*

(ii) the final good firm makes zero profits. Its demand functions for $i = 1, \ldots, N$ intermediate inputs and production labour are given by (5.3)*;*

(iii) intermediate firms set prices and quantities, and earn profits according to (A.2)*; they maximise their stock price* (B.8) *by choosing the drift and volatility of their quality process* (B.1) *according to the first-order conditions* (5.16)*;*

(iv) market-driven investors maximise (5.9) *subject to the law of motion* (B.4) *by choosing their portfolio share of each risky stock* $i = 1, \ldots, N$ *according to* (B.5)*;*

(v) liability-driven investors maximise (5.12) *subject to the modified law of motion in parallel to* (B.4) *and the constraint* (5.11) *by choosing the portfolio share of stocks* $i = 1, \ldots, N$ *according to* (B.5)*;*

(vi) product quality follows the Kolmogorov-forward equation (B.9)*;*

(vii) and the free entry condition (5.17) *holds;*

such that the markets for the final good, labour, the risk-free bond, N *intermediate goods, and* N *stocks described by* (A.7)*,* (A.8)*,* (A.9)*,* (A.10)*, and* (A.11) *clear.*

B.2.2 Solving for equilibrium

As before, I drop indexes to indicate symmetry across firms. I guess that a firm's price function is linear in the quality level $P(q) = Pq$, which implies that stock price volatility is the same as the underlying volatility of the quality level $\varsigma = \sigma(z)$ and $\varsigma^a = \sigma^a$. Investors' portfolio allocation will be symmetric across stocks:

$$X^M = \frac{\mu - r - z^e}{\gamma\left[\sigma(z)^2 + N\left(\sigma^a\right)^2 + z^e\right]} \qquad \text{and} \qquad X^L = \frac{\mu - r - z^e}{(2\kappa + \gamma)\left[\sigma(z)^2 + N\left(\sigma^a\right)^2 + z^e\right]}. \tag{B.10}$$

Denoting the wage relative to aggregate quality by ω as before, the firm's price function (B.8) collapses to:

$$\left[r + (1+\lambda)z^e + \lambda\left(\sigma^a\right)^2 N\right] P = \max_z \ \pi - \zeta z^\eta \omega + \left[z - \lambda\sigma(z)^2\right] P, \tag{B.11}$$

where the new term $\lambda\left(\sigma^a\right)^2 N$ parametrises the aggregate component on the risk premium. The equilibrium risk premium is:

$$\mu - r = (1+\lambda)z^e + \lambda\left[\sigma(z)^2 + N\left(\sigma^a\right)^2\right]. \tag{B.12}$$

C Appendix – Extended Model with Heterogeneous Firms

This Appendix extends the model presented in Section 5 and Appendix A by introducing heterogeneity among incumbent firms. Section C.1 describes the main changes in the extended model setup.

As the aggregate dynamics in the model with heterogeneous firms depend on the distribution of qualities, I derive the Kolmogorov-forward equation in Section C.2. This is non-trivial because the model features a discrete and finite number of firms, which implies that idiosyncratic shocks behave like aggregate shocks to the distribution, in particular shocks to individual firms change the weights across the firm size distribution for all firms. Finally, Section C.3 presents the model equilibrium.

C.1 Modified environment

C.1.1 Households and production

The structure of the household and production side remains unchanged as described in Sections 5.1.1 and 5.1.2.

C.1.2 Intermediate firms

Innovation. I introduce heterogeneity among firms via their R&D cost function. Following the standard setup in Akcigit and Kerr (2018) and Hobler and Matt (2024), firms innovate by investing $\zeta z_{it}^{\eta}\varphi^{\chi}$ of labour to generate a growth rate of their product quality at intensity z_{it}. The parameter χ captures the degree to which relative scale matters for the cost of innovation. An incumbent firm's innovation efficiency is:

$$\frac{\zeta z_{it}^{\eta} w_t}{z_{it} q_{it}} \left(\frac{q_{it}}{Q_t}\right)^{\chi} = \frac{\zeta z_{it}^{\eta-1} \omega_t}{\varphi_{it}^{1-\chi}}, \tag{C.1}$$

where $\omega_t \equiv w_t/Q_t$ is the wage-to-quality ratio. Equation (C.1) captures the quality improvement generated per unit of spending. When $\chi > 1$, larger firms closer to the frontier find it harder to innovate than laggards. When $\chi < 1$, the opposite is the case. The baseline model in Section 5 corresponds to $\chi = 1$. Firms' quality processes remain unchanged, see (5.5).

Stock returns. Stock returns are described by the process (5.6) with its coefficients as defined in (5.7).

C.1.3 Investors

Investors' problems remain the same as in the baseline model. Their demand functions are given by (5.10) and (5.13). As I discuss in the next section, the non-linear cost function introduces explicit price dependence of returns and therefore portfolio shares.

C.1.4 Stock price and investment

Firms maximise their stock price. In equilibrium, investors risk aversion gives rise to a risk premium. In the model with heterogeneous firms, this risk premium will depend on the firm size distribution. Imposing market clearing in each market, $\beta X_{it}^L + (1-\beta) X_{it}^M = 1$, yields the price function:

$$\max_{z_{it}} \left\{ \begin{array}{c} \pi(q_{it}) - \zeta z_{it}^{\eta} \varphi_{it}^{\chi} w_t + P'(q_{it}) z_{it} q_{it} + \frac{1}{2} P''(q_{it}) \left[\sigma(z_{it}) q_{it}\right]^2 \\ - \left[r + \lambda \varsigma_{it}^2 + (1+\lambda) z_{it}^e\right] P(q_{it}) \end{array} \right\} = 0. \tag{C.2}$$

The firm maximises (C.2) by choosing its research intensity z_{it} taking into account how its decision affects the risk premium. The firm's first-order condition is given by:

$$\zeta \eta z_{it}^{\eta-1} \varphi_{it}^{\chi} w_t + 2\varsigma_{it}^2 \lambda \left[\frac{\sigma'(z_{it})}{\sigma(z_{it})}\right] P(q_{it}) = P'(q_{it}) q_{it} + \frac{1}{2} P''(q_{it}) q_{it}^2 \sigma(z_{it}) \sigma'(z_{it}). \tag{C.3}$$

C.1.5 Closing the model

The remainder of the model parallels the baseline case. Free-entry and growth are described by (5.17) and (5.18). The market clearing condition for the final good is (A.7), the market clearing conditions for bonds, intermediate goods and stocks are given by (A.9) to (A.11). The labour market clearing condition is:

$$L = L_t^P + \sum_{i=1}^{N} \psi z_{it}^e \varphi_{it} + \sum_{i=1}^{N} \zeta z_{it}^{\eta} \varphi_{it}^{\chi}. \tag{C.4}$$

C.2 Deriving the Kolmogorov-forward equation

In the model with homogeneous firms, all firms choose the same innovation intensity. Creative destruction rates are symmetric. Hence, aggregates do not depend explicitly on the distribution of quality levels across firms. With heterogeneous firms, this is no longer the case. A Kolmogorov-forward equation (KFE) is needed to characterise the aggregate behaviour of the economy. It turns out that the model admits a stationary distribution in terms of firms' quality levels relative to the aggregate (or the mean). Given the vector $\boldsymbol{\varphi} = (\varphi_{1t}, \ldots, \varphi_{Nt})^T$, I denote the distribution of firms' relative quality levels by $p_t(\boldsymbol{\varphi})$.

Because there is only a discrete and finite number of N firms, deriving the KFE requires some additional steps compared to the baseline model or a model with a continuum of firms. In particular, shocks to individual firms now affect the distribution $p_t(\boldsymbol{\varphi})$ as they change the relative weights of firms $\boldsymbol{\varphi}$. Proposition 5 contains a description of the KFE and the step-by-step derivation.

Proposition 5 (Kolmogorov-forward equation with heterogeneous firms)**.** *Consider the model with heterogeneous firms described in Section C.1. Assume that the process for firms' product quality q_{it} follows* (5.5) *and aggregate quality Q_t is defined as in* (5.4)*. Then, the Kolmogorov-forward equation for the distribution $p_t(\boldsymbol{\varphi})$ of firms' relative quality level $\boldsymbol{\varphi} = (\varphi_{1t}, \ldots, \varphi_{Nt})^T$ with $\varphi_{it} = q_{it}/Q_t$ is given by:*

$$\begin{aligned} \frac{\partial p_t(\boldsymbol{\varphi})}{\partial t} = &- \sum_{i=1}^{N} \frac{\partial}{\partial \varphi_i} \left[c_{it}(\boldsymbol{\varphi}) p_t(\boldsymbol{\varphi}) \right] + \frac{1}{2} \sum_{i=1}^{N} \sum_{\ell=1}^{N} \frac{\partial^2}{\partial \varphi_i \partial \varphi_\ell} \left[B_{i\ell t}(\boldsymbol{\varphi}) p_t(\boldsymbol{\varphi}) \right] \\ &+ \sum_{i=1}^{N} z_{it}^e \left[\left(\frac{\nu^N}{D_{it}^{N+1}} \right) p_t\left(\boldsymbol{J}_{it}^{-1}(\boldsymbol{\varphi}) \right) - p_t(\boldsymbol{\varphi}) \right], \end{aligned} \tag{C.5}$$

where $D_{it} = \nu - (\nu - 1)\varphi_{it}$. The remaining coefficients are given by:

1. *a drift term:*

$$c_{it}(\boldsymbol{\varphi}) = \varphi_{it} \left(\left[z_{it} - \overline{z}_t(\boldsymbol{\varphi}) \right] + \left[\overline{\Sigma}_t(\boldsymbol{\varphi}) - \varphi_{it} \sigma_{it}^2 \right] \right), \tag{C.6}$$

   with average innovation intensity $\overline{z}_t(\boldsymbol{\varphi}) \equiv \sum_{j=1}^N \varphi_{jt} z_{jt}$ and variance $\overline{\Sigma}_t(\boldsymbol{\varphi}) \equiv \sum_{j=1}^N \varphi_{jt}^2 \sigma_{jt}^2$.

2. *a covariance term:*

$$B_{i\ell t}(\boldsymbol{\varphi}) = \begin{cases} \varphi_{it}^2 \left[(1 - \varphi_{it}) \sigma_{it}^2 + \sum_{j=1}^{N} (\varphi_{jt} \sigma_{jt})^2 \right] & \text{if } i = \ell, \\ \varphi_{it} \varphi_{\ell t} \left[\sum_{j=1}^{N} (\varphi_{jt} \sigma_{jt})^2 - \varphi_{it} \sigma_{it}^2 - \varphi_{\ell t} \sigma_{\ell t}^2 \right] & \text{if } i \neq \ell. \end{cases} \tag{C.7}$$

3. *and a jump vector $\boldsymbol{J}_{it}^{-1}(\boldsymbol{\varphi}) = \left(J_{i1t}^{-1}, \ldots, J_{iNt}^{-1} \right)^T$ with elements given by:*

$$J_{ijt}^{-1} = \begin{cases} \frac{\varphi_{jt}}{D_{it}} & \text{if } j = i, \\ \frac{\nu \varphi_{jt}}{D_{it}} & \text{if } j \neq i. \end{cases} \tag{C.8}$$

Proof. The evolution of weights depends on a continuous component $d\boldsymbol{\varphi}^c$ and a series of discontinuous Poisson jumps $\boldsymbol{J}_{it}^{-1}(\boldsymbol{\varphi})$. First, starting with the continuous part, the definition $\varphi_{it} \equiv q_{it}/Q_t$ together with Itô's lemma implies that:

$$d\varphi_{it}^c = \frac{dq_{it}^c}{Q_t} - \frac{q_{it}dQ_t^c}{Q_t^2} - \frac{d\langle q_{it}, Q_t\rangle}{Q_t^2} + \frac{q_{it}d\langle Q_t\rangle}{Q_t^3}. \tag{C.9}$$

Using $dq_{it}^c = q_{it}\left(z_{it}dt + \sigma_{it}d\mathcal{Z}_{it}\right)$, $dQ_t^c = \sum_{j=1}^N q_{jt}\left(z_{jt}dt + \sigma_{jt}d\mathcal{Z}_{jt}\right)$, $d\langle q_{it}, Q_t\rangle = q_{it}^2\sigma_{it}^2 dt$, and $d\langle Q_t\rangle = \sum_{j=1}^N q_{jt}^2\sigma_{jt}^2 dt$ yields:

$$d\varphi_{it}^c = \varphi_{it}\Big(\left[z_{it} - \overline{z}_t(\boldsymbol{\varphi})\right] + \left[\overline{\Sigma}_t(\boldsymbol{\varphi}) - \varphi_{it}\sigma_{it}^2\right]\Big)dt + \varphi_{it}\left(\sigma_{it}d\mathcal{Z}_{it} - \sum_{j=1}^N \varphi_{jt}\sigma_{jt}d\mathcal{Z}_{jt}\right), \tag{C.10}$$

where $\overline{z}_t(\boldsymbol{\varphi}) \equiv \sum_{i=1}^N \varphi_{it}z_{it}$ and $\overline{\Sigma}_t(\boldsymbol{\varphi}) \equiv \sum_{j=1}^N \varphi_{jt}^2\sigma_{jt}^2$ as used in Proposition 5. Define the first term in parentheses as $c_{it}(\boldsymbol{\varphi}) \equiv \varphi_{it}\Big(\left[z_{it} - \overline{z}_t(\boldsymbol{\varphi})\right] + \left[\overline{\Sigma}_t(\boldsymbol{\varphi}) - \varphi_{it}\sigma_{it}^2\right]\Big)$ in (C.6) and note that the variance term can be written as $\sum_{j=1}^N G_{ij}(\boldsymbol{\varphi})d\mathcal{Z}_{jt} = \varphi_{it}\sum_{j=1}^N\left(\sigma_{it}\mathbf{1}_{i=j} - \varphi_{jt}\sigma_{jt}\right)d\mathcal{Z}_{jt}$, or equivalently:

$$d\varphi_{it}^c = c_{it}(\boldsymbol{\varphi})dt + \sum_{j=1}^N G_{ij}(\boldsymbol{\varphi})d\mathcal{Z}_{jt}. \tag{C.11}$$

As the liquidity shocks in the model are uncorrelated across firms, the diffusion covariance matrix between product lines is simply:

$$\boldsymbol{B}_t(\boldsymbol{\varphi}) = \boldsymbol{G}_t(\boldsymbol{\varphi})\boldsymbol{G}_t(\boldsymbol{\varphi})^T, \tag{C.12}$$

where the elements are defined in (C.7).

Second consider the jump part of the process for φ_{it} driven by creative destruction from outsiders that improve the quality of an existing product by a deterministic step size $\nu - 1$. Define $\boldsymbol{\Lambda}_{it}(\boldsymbol{\varphi})$ as the Jacobian of the shares related to the jumps. When one firm j experiences a jump, the aggregate quality level Q_t moves to $Q_t^+ = Q_t + (\nu-1)q_{jt} = \left[1 + (\nu-1)\tilde{\varphi}_{it}\right]Q_t$, where $\tilde{\varphi}_{it}$ is the quality ratio before the jump. Writing the post-jump shares as φ_{it}, the mappings between shares for firm i given a jump of j before, $J_{it}(\tilde{\boldsymbol{\varphi}})$, and after the jump, $J_{it}^{-1}(\boldsymbol{\varphi})$, are:

$$J_{it}(\tilde{\boldsymbol{\varphi}}) = \begin{cases} \frac{\nu\tilde{\varphi}_{it}}{1+(\nu-1)\tilde{\varphi}_{jt}} & \text{if } i = j, \\ \frac{\tilde{\varphi}_{it}}{1+(\nu-1)\tilde{\varphi}_{jt}} & \text{if } i \neq j, \end{cases} \quad \text{and} \quad J_{it}^{-1}(\boldsymbol{\varphi}) = \begin{cases} \frac{\varphi_{it}}{\nu-(\nu-1)\varphi_{jt}} & \text{if } i = j, \\ \frac{\nu\varphi_{it}}{\nu-(\nu-1)\tilde{\varphi}_{jt}} & \text{if } i \neq j. \end{cases} \tag{C.13}$$

To economise on notation, I write $D_{it} = \nu - (\nu - 1)\tilde{\varphi}_{it}$ and collect terms in the jump vector $\boldsymbol{J}_{it}^{-1}(\boldsymbol{\varphi}) = \left(J_{i1t}^{-1}, \ldots, J_{iNt}^{-1}\right)^T$. To find the Jacobian $\boldsymbol{\Lambda}_{it}(\boldsymbol{\varphi})$ needed for (C.5), collect terms in a $N \times N$ matrix:

$$\boldsymbol{\Lambda}_{it} = \frac{\nu}{D_{it}} \mathcal{I}_{N\times N} + \boldsymbol{u}_{it} \boldsymbol{e}_i^T, \tag{C.14}$$

where $\boldsymbol{e}_i = (0, \ldots, 0, 1, 0, \ldots, 0)^T$ has zeroes everywhere but the i^{th} position, and $\boldsymbol{u}$ is:

$$\boldsymbol{u}_{it} = \begin{cases} \frac{\nu(1-D_{it})}{D_{it}^2} & \text{if } j = i, \\ \frac{\nu(\nu-1)\varphi_{jt}}{D_{it}^2} & \text{if } j \neq i, \end{cases} \tag{C.15}$$

such that $\boldsymbol{u}_{it}\boldsymbol{e}_i^T$ is an $N \times N$ matrix. Intuitively, (C.14) has diagonal elements $\Lambda_{\ell\ell} = \nu/D_i^2$ for $\ell \neq i$, that is, the lines where no jump occurred but whose weight shifts due to a jump on another line i, and $\Lambda_{ii} = \nu/D_i$ for the row that corresponds to the element where the jump occurred. The off-diagonal elements are zero apart from the ℓ^{th} column with $\Lambda_{i\ell} = \nu(\nu - 1)\varphi_{it}/D_i^2$ for $\ell \neq i$, reflecting how the jump changes the numerator of the share in (C.13).

To apply the change-of-variable formula when deriving the KFE, the determinant of this Jacobian is needed. We have:

$$\det(\boldsymbol{\Lambda}_{it}) = \det\left(\frac{\nu}{D_{it}} \mathcal{I}_{N\times N}\right)\left[1 + \boldsymbol{e}_i^T \left(\frac{\nu}{D_{it}} \mathcal{I}_{N\times N}\right)^{-1} \boldsymbol{u}_{it}\right] = \frac{\nu^N}{D_{it}^{N+1}}. \tag{C.16}$$

Finally, collect the drift (C.6), the covariance (C.7), and the Jacobian (C.16) to obtain the KFE in (C.5).

□

C.3 Equilibrium

We can now discuss the equilibrium in this economy. I will first formally define the growth path and then derive firms' equilibrium innovation.

C.3.1 Equilibrium definition

Definition 3. *The economy is on a stochastic balanced growth path if all aggregate variables – output Y_t, consumption C_t, profits Π_t, wages w_t, and intermediate production costs Y_t^P – grow at a common expected growth rate g_t, the growth rate of aggregate quality Q_t defined in (5.18); the risk-free rate is constant at r, the risk-neutral household's discount rate defined in*

(5.1)*; and stock returns follow the process in* (5.6)*. Agents' optimisation problems satisfy the following conditions:*

(i) *households choose consumption and savings according to* (5.1)*;*

(ii) *the final good firm makes zero profits. Its demand functions for* $i = 1, \dots, N$ *intermediate inputs and production labour are given by* (5.3)*;*

(iii) *intermediate firms set prices and quantities, and earn profits according to* (A.2)*; they maximise their stock price* (C.2) *by choosing the drift and volatility of their quality process* (5.5) *according to the first-order conditions* (C.3)*;*

(iv) *market-driven investors maximise* (5.9) *subject to the law of motion* (5.8) *by choosing their portfolio share of each risky stock* $i = 1, \dots, N$ *according to* (5.10)*;*

(v) *liability-driven investors maximise* (5.12) *subject to a law of motion equivalent to* (5.8) *and* (5.11) *by choosing the portfolio share of stocks* $i = 1, \dots, N$ *according to* (5.13)*;*

(vi) *product quality follows the Kolmogorov-forward equation* (C.5)*;*

(vii) *and the free entry condition* (5.17) *holds;*

such that the markets for the final good, labour, the risk-free bond, N *intermediate goods, and* N *stocks described by* (A.7)*,* (C.4)*,* (A.9)*,* (A.10)*, and* (A.11) *clear.*

C.3.2 Solving for equilibrium

The firms' first-order condition (C.3) implies that innovation choices are no longer symmetric. Consequently, the model does not have a closed form solution. Nevertheless, there exists a stationary distribution of relative quality levels $p(\varphi)$ and the model can be solved numerically. A future version of this paper will contain the numerical solution under a suitable calibration.

D Appendix – Quantitative Model

D.1 Calibration procedure

This Appendix contains further notes on the calibration procedure in Section 6.1. The model features twelve structural parameters as listed in Table 6.1. I set $L = 1$ and $\kappa = 1$ to normalise the size of the economy and the initial penalty on pension funds. Moreover, we have $\eta = 2.5$, $\vartheta = 0.6$, and $r = 0.05$. I then set $\beta = 0.25$ such that, given a portfolio share $\alpha = 0.47$, the implied shareholding of liability-driven investors is $\beta X^L / [(1-\beta)X^L + \beta X^M] = \beta \alpha^L W_t^L / Q_t \approx 0.12$, see (5.20). Next, the equilibrium portfolio share in equation (A.6) is $\alpha^L = \lambda/(2\kappa + \gamma)$. Using the definition of $\lambda = \gamma(2\kappa+\gamma)/[2\kappa(1-\beta)+\gamma]$, one can invert the portfolio share expression to back out the value of γ that supports the targeted portfolio share given the other parameter values:

$$\gamma = 2\kappa(1-\beta)\left(\frac{\alpha^L}{1-\alpha^L}\right). \tag{D.1}$$

Having set the externally-calibrated parameters, the vector of moment conditions for the internal calibration is:

$$\mathcal{M}(\Gamma) = [g, \quad z^e, \quad \varepsilon, \quad m]^T, \tag{D.2}$$

where $m = \mu - z^e - r$ is the risk premium and $\varepsilon \equiv -N^{-1}\sum_{i=1}^N d\ln\left(\zeta z_{it}^\eta \omega\right)/d\kappa$ is the elasticity of innovation expenditure with respect to the change in investor composition as defined in (6.3), respectively. To derive this object, start from the first-order condition $\eta\zeta\nu z_{it}^{\eta-1} = \psi\phi(z_{it})$ where $\phi(z_{it}) = 1 - 2\lambda\sigma(z_{it})\sigma'(z_{it})$ and $\sigma(z_{it}) = z_{it}^{\underline{\sigma}}$. Totally differentiate with respect to z_{it} and λ to obtain:

$$\frac{dz_{it}}{d\lambda} = -\frac{2\underline{\sigma}\psi z_{it}}{\eta\zeta\nu(\eta-1)z_{it}^{\eta-2\underline{\sigma}} + 2\underline{\sigma}\psi\lambda(2\underline{\sigma}-1)} = -\frac{2\underline{\sigma} z_{it}}{(\eta-1)z_{it}^{1-2\underline{\sigma}} + 2\underline{\sigma}\lambda(2\underline{\sigma}-\eta)}. \tag{D.3}$$

where the second equality uses $\eta\zeta\nu z_{it}^{\eta-1} = \psi\left(1 - 2\underline{\sigma}\lambda z_{it}^{2\underline{\sigma}-1}\right)$ from the first-order condition. Similarly, differentiate the risk premium parameter λ with respect to the penalty κ to obtain $D \equiv d\lambda/d\kappa = 2\gamma\beta/[2\kappa(1-\beta)+\gamma]^2$. Putting everything together:

$$\varepsilon = -\frac{1}{N}\sum_{i=1}^N \frac{D}{\eta z_{it}}\left(\frac{2\underline{\sigma} z_{it}}{(\eta-1)z_{it}^{1-2\underline{\sigma}} + 2\underline{\sigma}\lambda(2\underline{\sigma}-\eta)}\right) = -\frac{1}{N}\sum_{i=1}^N \frac{\eta D}{(\eta-1)\delta_{it} + 2\underline{\sigma} - 1}, \tag{D.4}$$

where $\delta_{it} \equiv z_{it}^{1-2\underline{\sigma}}/(2\underline{\sigma}\lambda) - 1$. Given the theoretical moments in (D.2), I run the pattern search algorithm as described in (6.2). The parameters are $\{\underline{\sigma}, \nu, \psi, \zeta\}$. I use a weighting matrix $\boldsymbol{W} = [1, 1, 1, 1]$ and the Euclidean norm $p = 2$.

D.2 Untargeted moments

To provide a sense of the model's quantitative fit, I report a series of untargeted moments implied by the baseline calibration. The model-implied average annual return on firms' stock μ is 15.76 precent. The risk premium is approximately 6.7 percent.

The implied annual volatility of stock prices is 20.6 percent, which is approximately 5.96 percent on a monthly basis. Damodaran (2019) reports a monthly standard deviation of risk premiums of 5.78 percent for the period between 1981 to 2001, which is 20.02 per year. In the model, the risk premium is split between an idiosyncratic and a creative destruction component. In the baseline calibration, 95 percent of stock price volatility comes from creative destruction risk and the remaining 5 percent from firms' idiosyncratic cash flow volatility driven by their liquidity shocks.

At the firm level, the model implies a price earnings ratio of $P_t q_{it}/(\pi_t q_{it} - \zeta z^{\eta} w_t \varphi_{it})$ of approximately 10.4, which is at the lower end of estimates for the U.K. economy in the late 1990s and early 2000s.

Labour used in the production of the final good is $L^P = 0.85$, which implies that around 15 percent of workers are employed in the research sector. Total research spending is defined as $\sum_{i=1}^{N} \left[\psi z_{it}^{e} + \zeta z_{it}^{\eta}\right] \varphi_{it} w_t / Y_t$ and accounts for 22 percent of GDP, which is much larger than in the data but not surprising given that the model is a Schumpeterian growth model that abstracts from capital accumulation.

D.3 Output and risk premium

Figure D.1 shows the behaviour of output and the risk premium, which has been omitted from the main text. The left panel shows output Y as a function of the regulatory constraint parameter κ. Tighter regulation on liability-driven investors raises contemporaneous output through its impact on incumbent firms' labour demand and hence the equilibrium wage. When incumbent firms cut back on investment, the equilibrium wage drops, allowing intermediate producers to increase their output. In the baseline calibration, however, output is relatively inelastic with respect to changes in the regulatory constraint. This is because most labour is used for production already, $L^P = 0.85$.

The right panel of Figure D.1 shows the risk premium, defined as $\mu - r - z^e$, as a function of the regulatory constraint parameter κ. The risk premium is increasing in κ in the

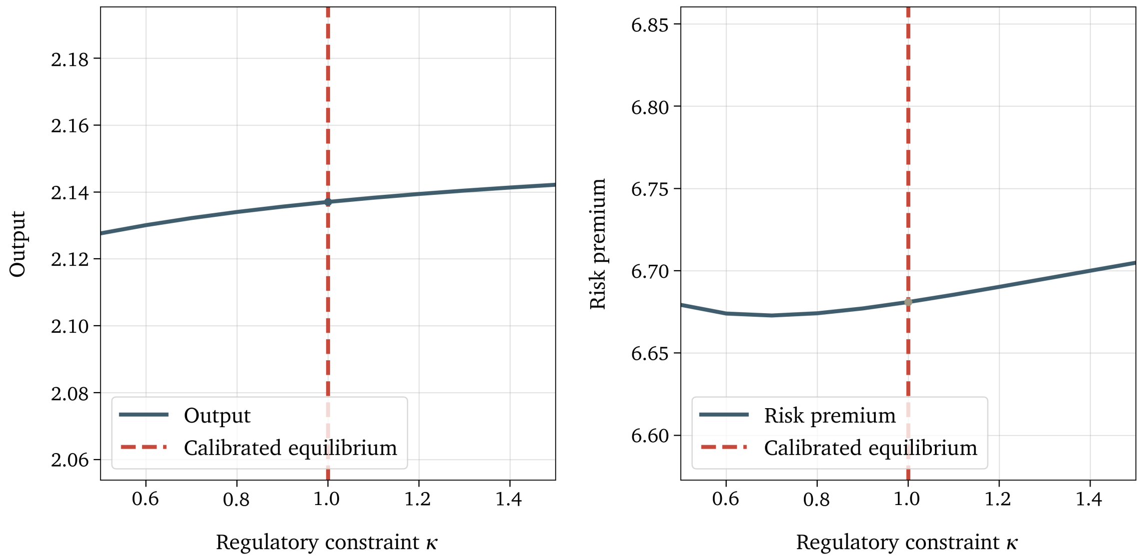


Figure D.1: Equilibrium output and risk premium.

The figure shows output (left) and risk premia (right) as a function of the regulatory constraint parameter κ. The red line denotes the calibrated pre-reform steady state.

neighbourhood of the parameter changes considered in the model, but can locally decrease when firms overreact to changes in market risk aversion as explained in the Section 5. In the baseline calibration, is true for small values of $\kappa < 0.6$. This result is driven by the functional form assumption in (6.1), $\sigma(z) = z^{\underline{\sigma}}$. The implied value from internal calibration is $\underline{\sigma} = 0.54$. For more convex functional forms, the risk premium is increasing on the entire domain of κ.

E Appendix – Institutional Background

E.1 Industry overview

Memberships and size. In 2002, the U.K. pension sector held approximately £3 trillion, or around 125 percent of GDP, in assets. One-third of assets were held in DB schemes, with two-thirds of that fraction in public schemes. In total, DB pension schemes managed the retirement benefits of around 20 million members. Six million were enrolled in a public sector DB scheme.

The distribution of assets is highly left-skewed. Even though there are fewer than 400 funds with more than 5,000 members, more than 75 percent of pension assets are concentrated at those funds, which tend to be public schemes. The largest pension fund, the Universities Superannuation Scheme (USS), which covers the higher education sector, has around 560,000 members and approximately £75 billion in pension assets. In contrast, the almost 6,000 small funds with fewer than 100 members account for only 2.5 percent of total pension assets. To illustrate the skewness of the size distribution, the left panel of Figure E.1 shows a histogram of pension fund size in 2004 prior to the reform. The right panel shows cumulative assets at market value and discounted liabilities (future pension obligations) by fund-size bin for the same year.

Defined-benefit schemes. Defined-benefit schemes are concentrated in the public sector and among few large corporations. Over the last two decades, the number of private sector DB schemes has been steadily declining. In 2024, there were around 5,200 private defined-benefit schemes, down from approximately 11,000 in 2004 (The Pensions Regulator, 2024).

Local government pension schemes. On top of the large number of private schemes, there are more than 100 public-sector pension schemes, comprising large schemes such as the National Health Service, Military, and Teachers' Pension Schemes, as well as 99 local government pension schemes (LGPS) in England and Wales, eleven such schemes in Scotland, and one in Northern Ireland.Some pension funds operate sub-funds for certain member groups. In 2002, there were 99 consolidated LGPS. Richmond-upon-Thames pension fund merged with Wandsworth in 2016.

These LGPS managed the pensions of local government employees and other eligible organisations, including public sector bodies and certain charities. LGPS are statutory DB schemes entitling members to payouts at age 65. There is substantial variation among LGPS in terms of size, ranging from the smallest fund, Kensington and Chelsea Pension Fund

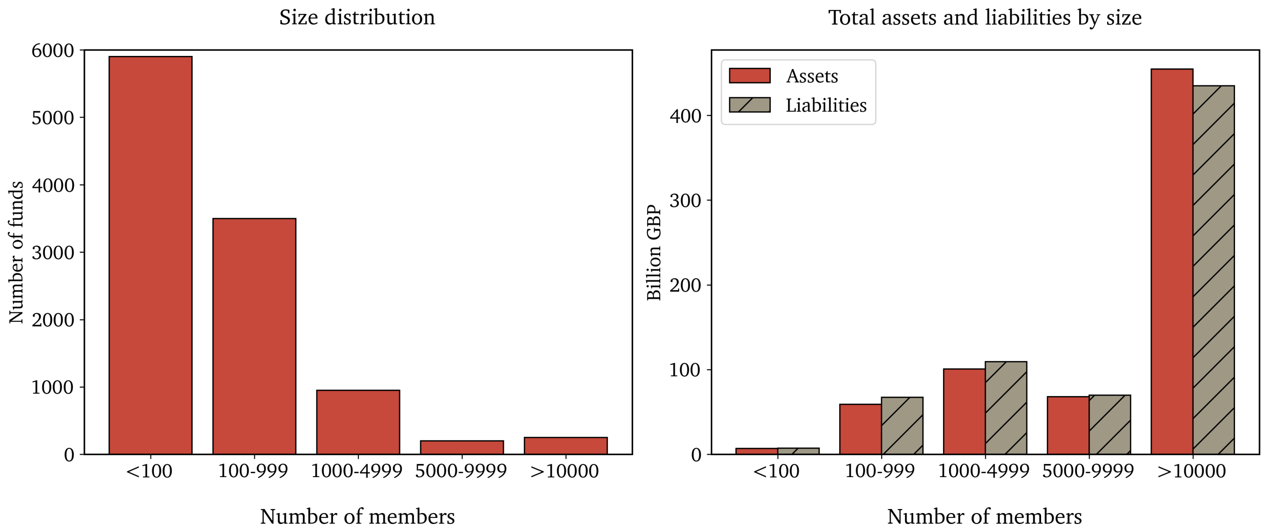


Figure E.1: Pension fund size distribution in 2002.

with 7,395 members and £250 million in assets, to Greater Manchester Pension Fund with 207,972 members and about £6.5 billion in assets. In 2002, these LGPS had around 4 million members and approximately £200 billion in assets under management.

E.2 Pensions reform in the U.K.

E.2.1 The Pensions Act 1995

The first wave of reforms began amidst the collapse of the *Maxwell Communication Corporation* after the death of its founder, the publisher Robert Maxwell, in 1991. It later emerged that Maxwell and his advisers had tapped the group's pension fund to issue loans to Maxwell's private companies and then used the collateral from those loans to shore up the group's share price. Further investigation revealed a hole of more than £420m in the group's pension fund (Desmond, 1992). The government subsequently commissioned the Pensions Law Review headed by Sir Royston Goode QC. The *Goode Review* recommended stronger regulation of fund risk-taking and tighter supervision of defined-benefit schemes' funding status (Goode, 1993).

Following the review, the Pensions Act 1995 codified a series of governance reforms. The most impactful legislative change was the introduction of the *Minimum Funding Requirement* (MFR), intended to provide protection for scheme members by setting a benchmark for the acceptable level of scheme assets relative to future pension obligations. Under the MFR, defined-benefit pension schemes were required to value scheme assets on a mark-to-market basis. Future obligations would be valued using the long end of the gilts curve adjusted for a market factor to reflect expected U.K. equity dividend yields. When the market value of a fund's assets fell short of its future obligations, the pension fund was declared *underfunded* and became subject to regulatory investigation. To monitor compliance with the new legal framework, an independent regulator, the *Occupational Pensions Regulatory Authority* (OPRA), was established.

The MFR came into effect in April 1997. Its implementation, however, coincided with another legislative change, the abolition of the dividend tax credit in the 1997 Budget, which had so far allowed pension funds favourable treatment of dividends on their equity holdings. With domestic and overseas equities constituting 80 percent of U.K. pension fund assets at the time, this meant that pension funds had become more exposed to the short-term volatility of equity prices. At the same time, lower government debt issuance because of a cyclical improvement in the U.K.'s fiscal position reduced long gilt yields and led to an increase in funds' deficits under MFR (Barclays Capital Research, 2005, 2006).

The reform was met with widespread resistance and many DB funds started to review their long-term investment strategies. In March 1999, the Treasury announced that – amidst the strong objections to MFR – it had commissioned the Institute of Actuaries to review the suitability and risks of enforcing the funding requirements. The panel's consensus view was that the MFR effectively forced trustees to "*pay too much attention to short-term market movements*" and had created "*extra demand at the long end of the gilts market*", thereby artificially compressing yields (Faculty of Actuaries and Institute of Actuaries, 2000, p. 1). In a concurrent consultation process, the Association of British Insurers, the National Association of Pension Funds, and the Association of Consulting Actuaries all called for the MFR to be scrapped (Thurnley, 2008, p. 8). Following the review's recommendations, the MFR was suspended and replaced with a relatively lenient temporary valuation measure, which effectively returned the sector to the status quo ante (Barclays Capital Research, 2005).

In March 2001, the findings of a parallel, more comprehensive report into the institutional investment sector, led by former Gartmore chief executive Sir Paul Myners, was presented to the public. The *Myners Review* questioned the investment practice of pension fund managers and trustees, but also argued that "*the MFR distorts investment decision-making by its use of (...) U.K. quoted equities and gilts* [to calculate discount rates]". Although pension funds were not required to invest in these assets, doing so allowed them to "*minimise volatility against the funding standard*" (Myners, 2001, p.12). In the March 2001 Budget, Chancellor Gordon Brown announced the abolition of the MFR, stating the government's intention to replace it with a more tailored funding requirement as part of a new pension reform (HM Treasury, 2001, Sec. 3.48).

E.2.2 Post-2004 reforms

The final phase of reforms came in the aftermath of the global financial crisis of 2008-2009. The Pensions Act 2008 brought auto-enrolment, which was rolled out from 2012, minimum employer contribution requirements, and the introduction of a series of minimum quality requirements for workplace pensions. The Act also established the National Employment Savings Trust (NEST), a fall-back option for smaller employers and workers on lower incomes.

Finally, a series of subsequent Acts (2014, 2015, 2017 and 2021) focused on updated rules for DC pension schemes. As for DB pension schemes, the Pension Schemes Act 2021 gave TPR enhanced enforcement and investigative powers, among other changes. The regulators ability to demand additional asset injections into underfunded pension schemes was strengthened.

F Appendix – Data

This Appendix supplements Section 2. Appendix F.1 contains further details on the data construction process. Appendix F.2 presents descriptive statistics on the fund-level data, and Appendix F.4 provides an overview of pension schemes investment mandates.

F.1 Further details on data construction

This appendix contains further information on the three main strategies used to construct the holdings data that I have described in Section 2.2.

Strategy I: Direct holdings data. A subset of LGPS funds report direct holdings data in their annual valuation reports. Figure F.1 shows an excerpt from one such report for a pension scheme in my sample. The data typically contains information on the sector, company clear name, size and value of the position, and an identifier, in this case the ticker. Some funds provide other identifiers such as CUSIPs or ISINs. I disregard non-equity holdings as well as all non-UK equity funds. Finally, I harmonise names across different funds and map identifiers into COMPUSTAT GVKEYs to match with companies' balance sheet data and stock price data from CRSP.

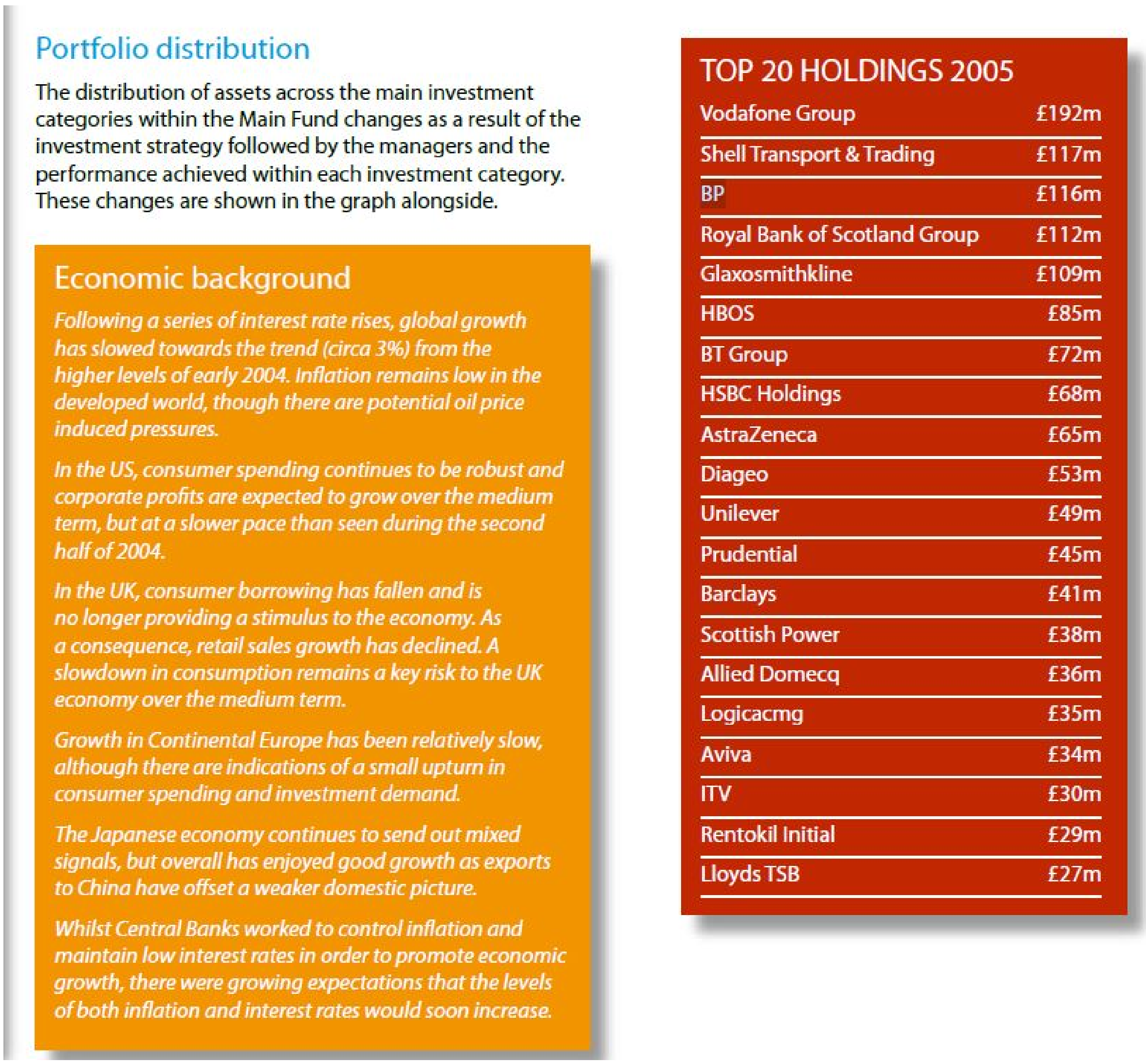
MARCH 2005 PORTFOLIO VALUATION					
UK EQUITIES					
Sector	**Company Name**	**TICKER_A**	**Number held**	**Mkt Price Pence**	**Total £**
MINING					
UK Mining	ANGLO AMER US$0.50	aal ln equit	350,000	1255.00	4,392,500
UK Mining	RIO TINTO 10P	rio ln equity	490,000	1711.00	8,383,900
UK Mining Total					**12,776,400**
OIL & GAS					
UK Oil & Gas	BG GROUP ORD 10P	bg/ ln equit	1,625,000	411.25	6,682,813
UK Oil & Gas	BP PLC USD$0.25	bp/ ln equit	9,900,000	548.50	54,301,500
UK Oil & Gas	SHELL ORD25P	shel ln equi	5,300,000	475.00	25,175,000
UK Oil & Gas Total					**86,159,313**

Figure F.1: A snipped from a valuation report.

Strategy II: Annual report data. Most funds report partial holdings in their annual reports or one of the appendices. The degree to which pension funds report stock-level holding data varies. Most funds report their top-10, top-20 or top-100 domestic and overseas stock holdings. Figure F.2 contains an example from the appendix of an annual report.

These tables only list the name of the corporation that issues the stock and the valuation at the pension funds' balance sheet date, that is, 31 March of each year. To back out quantities, I add market prices at the balance sheet date from LSEG. I then manually match company names with firm identifiers to harmonise my data with the holdings data from Strategy I.

Naturally, this strategy only gives me an incomplete picture of the funds' portfolio holdings, which is why, for most funds, I combine Strategy II with Strategy III below.



Portfolio distribution

The distribution of assets across the main investment categories within the Main Fund changes as a result of the investment strategy followed by the managers and the performance achieved within each investment category. These changes are shown in the graph alongside.

Economic background

Following a series of interest rate rises, global growth has slowed towards the trend (circa 3%) from the higher levels of early 2004. Inflation remains low in the developed world, though there are potential oil price induced pressures.

In the US, consumer spending continues to be robust and corporate profits are expected to grow over the medium term, but at a slower pace than seen during the second half of 2004.

In the UK, consumer borrowing has fallen and is no longer providing a stimulus to the economy. As a consequence, retail sales growth has declined. A slowdown in consumption remains a key risk to the UK economy over the medium term.

Growth in Continental Europe has been relatively slow, although there are indications of a small upturn in consumer spending and investment demand.

The Japanese economy continues to send out mixed signals, but overall has enjoyed good growth as exports to China have offset a weaker domestic picture.

Whilst Central Banks worked to control inflation and maintain low interest rates in order to promote economic growth, there were growing expectations that the levels of both inflation and interest rates would soon increase.

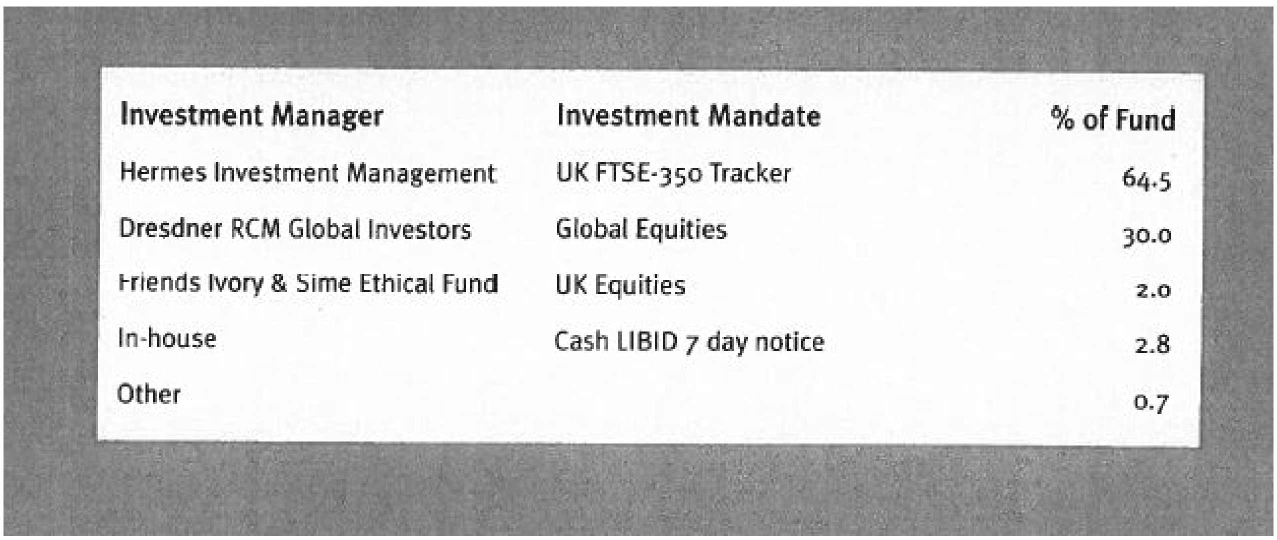
TOP 20 HOLDINGS 2005

Vodafone Group	£192m
Shell Transport & Trading	£117m
BP	£116m
Royal Bank of Scotland Group	£112m
Glaxosmithkline	£109m
HBOS	£85m
BT Group	£72m
HSBC Holdings	£68m
AstraZeneca	£65m
Diageo	£53m
Unilever	£49m
Prudential	£45m
Barclays	£41m
Scottish Power	£38m
Allied Domecq	£36m
Logicacmg	£35m
Aviva	£34m
ITV	£30m
Rentokil Initial	£29m
Lloyds TSB	£27m

Figure F.2: An annual report with top holdings data.

Strategy III: Asset managers data. LGPS typically delegate their portfolio management to external asset managers. In either the annual report or the valuation report, the pension fund discloses the name and mandate of the appointed manager, the amount of assets under management, and often also includes a reference to the specific investment products or funds that the LGPS is invested in.

Figure F.3 contains an excerpt from a pension fund annual report which specifies that *Hermes Investment Management* has been appointed as its asset manager. The investment mandate is for a *U.K. FTSE-350 Tracker* and the amount invested is 64.5 percent of the pension fund's assets. Similarly, the pension fund also invests 30 percent of its assets in *Global Equities Tracker* from *Dresdner RCM Global Investors*, 2 percent in an *Ivory & Sime Ethical U.K. Equity Fund*. Throughout, I restrict my analysis to equity funds that are either labelled as U.K. or global equity funds.



Investment Manager	Investment Mandate	% of Fund
Hermes Investment Management	UK FTSE-350 Tracker	64.5
Dresdner RCM Global Investors	Global Equities	30.0
Friends Ivory & Sime Ethical Fund	UK Equities	2.0
In-house	Cash LIBID 7 day notice	2.8
Other		0.7

Figure F.3: An annual report with asset manager mandate.

After digitising the fund-level allocation across asset managers, I proceed to construct the holdings data and match it with balance sheet data in several steps:

(i) Using FACTSET's mutual fund holdings data, I fuzzy match asset manager names to mutual fund names. For instance, for Hermes Investment Management's U.K. FTSE-350 Tracker I input *Hermes* and *FSTE-350 Tracker* into the fuzzy matching procedure. I then manually select the closest match. I resolve multiple potential matches or conflicts, by drawing on the description of asset manager investment mandates provided in pension funds' annual report.

(ii) Some asset managers cannot be identified in FACTSET. For missing funds, I repeat the procedure with MORNINGSTAR data.

(iii) Many mutual funds hold shares in other mutual funds. Using FACTSET IDs, I iteratively resolve cross holdings between mutual funds.

(iv) For those pension funds in the sample who have provided top-10 or top-20 holdings data, I cross-check that the total value of holdings for each stock reported in the annual report match the value of the holdings that I have reconstructed in steps (i) to (iii).

(v) I use a cross walk to map FACTSET identifiers into GVKEYs to identify firms in COMPUSTAT. I then match on the GVKEY.

F.2 Descriptive statistics

This Appendix contains descriptive statistics for fund portfolios and further summary statistics on the distribution of the shift-share instrument constructed from those portfolios.

F.2.1 Balance sheet data

Table F.1 reports summary statistics for the LGPS balance sheet data. In 2002/2003, the average pension fund in the sample held £1.814 billion in assets which grew to £3.455 billion in 2006/2007. The average funding level, defined as the ratio of a pension fund's market value of assets to the present value of future pension obligations, was 0.92 in 2001/2002 and 0.84 in 2006/2007. Hence, the average fund was *underfunded* as defined under the SFO. In fact, in 2002/2003 there were only 11 funds with a funding level over 100 percent. Figure 3.1 shows the cross-sectional distribution of LGPS funding levels for the valuation cycle before the Pensions Act 2004 came into effect.

In 2002/2003, the average portfolio share was 42 percent for U.K. equity and 25 percent for overseas equity. The domestic share well to 0.36 percent in 2006/2007 while the overseas share rose to 31 percent. For comparison, the average pension scheme (public and private) saw a decrease in its U.K. equity holdings from 38 percent to 25 percent over the same period. While LGPS held larger shares of U.K. equities, the scale of the decline was similar. Figure F.4 shows the equity portfolio share for the pension funds in my sample for each financial year 2001/2002 to 2005/2006. Funds are ordered alphabetically.

F.2.2 Regional distribution

In total there are 98 LGPS across England, Scotland, Wales and Northern Ireland. The map in Figure 3.1 shows the distribution of funding levels by location. 33 of these 98 schemes are based in London. Richmond's pension scheme merged with the neighbouring Wandsworth in 2016 and is treated for the purposes of this paper as a separate pension scheme. Figure F.6 shows the distribution of funding levels for the London-based schemes.

Table F.1: Fund data summary statistics pre and post reform

	FY 2002/2003					FY 2006/2007				
	Mean	Std	P25	P50	P75	Mean	Std	P25	P50	P75
Active members	39926.66	30815.05	15650.84	29177.24	50154.55	43165.88	32700.89	18597.26	32028.19	53180.54
Total members	79155.39	62613.12	30143.21	56863.26	99483.67	91786.12	70726.97	38234.66	65770.56	112547.11
Net assets	1814.20	1626.39	567.39	1097.59	2202.74	3455.45	3040.65	1139.79	2182.32	3887.51
Investments	1788.07	1600.46	557.79	1092.67	2188.54	3431.98	3011.88	1133.66	2168.70	3871.85
Funding level	0.92	0.12	0.85	0.92	0.99	0.84	0.08	0.79	0.84	0.89
Bonds	0.19	0.06	0.15	0.19	0.23	0.18	0.06	0.14	0.16	0.20
UK equity	0.42	0.06	0.39	0.43	0.46	0.36	0.06	0.33	0.36	0.39
Overseas equity	0.25	0.05	0.21	0.24	0.29	0.31	0.06	0.26	0.31	0.35
Property	0.07	0.04	0.05	0.07	0.10	0.08	0.04	0.06	0.09	0.10
Other	0.07	0.07	0.03	0.04	0.09	0.08	0.07	0.03	0.06	0.09

This table shows summary statistics for the 98 Local Government Pension Schemes in my sample. The data are reported for the financial year 2001/2002, before the Pensions Act 2004 was announced, and the financial year 2006/2007, after the Act came into effect. Net assets and investments are reported in million pounds sterling. Bonds, equities, property, and others are reported as portfolio shares.

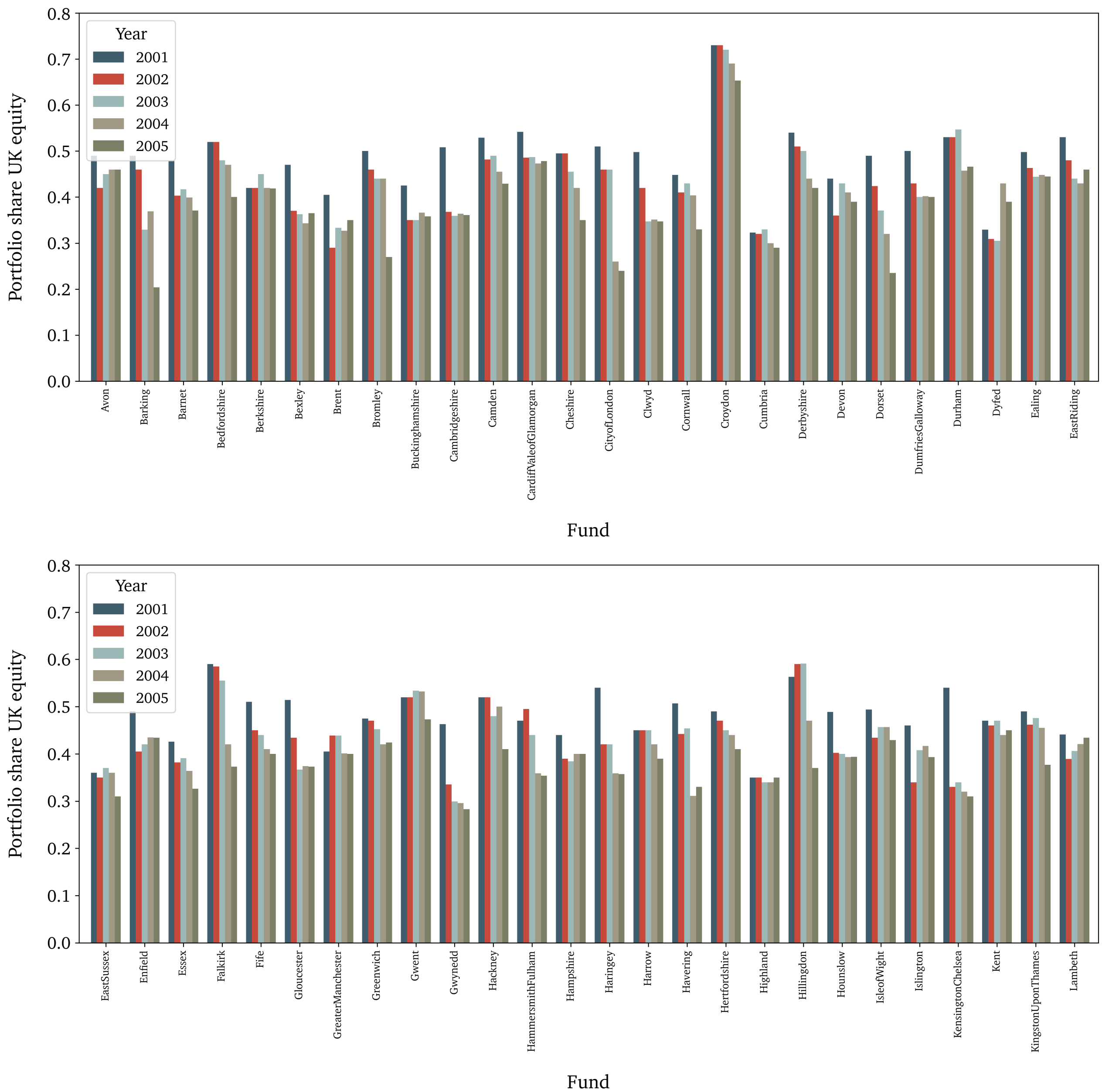


Figure F.4: U.K. equity portfolio share by fund, part I/II.

This figure shows the U.K. equity portfolio share for the financial years 2001/2002 to 2005/2006 for LGPS Avon to Lambeth in alphabetical order.

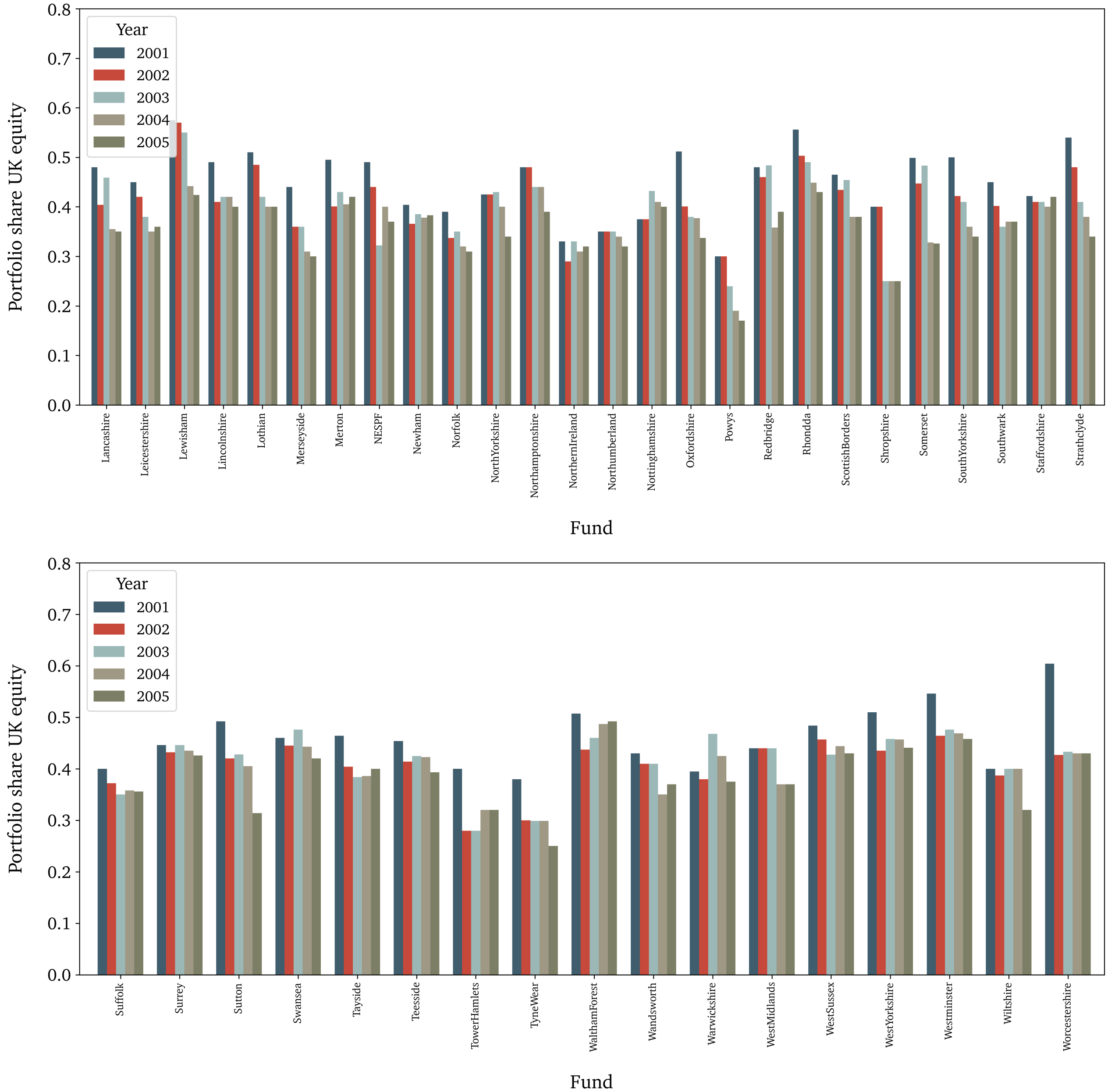


Figure F.5: U.K. equity portfolio share by fund, part II/II.

This figure shows the U.K. equity portfolio share for the financial years 2001/2002 to 2005/2006 for LGPS Lancashire to Worcestershire in alphabetical order.

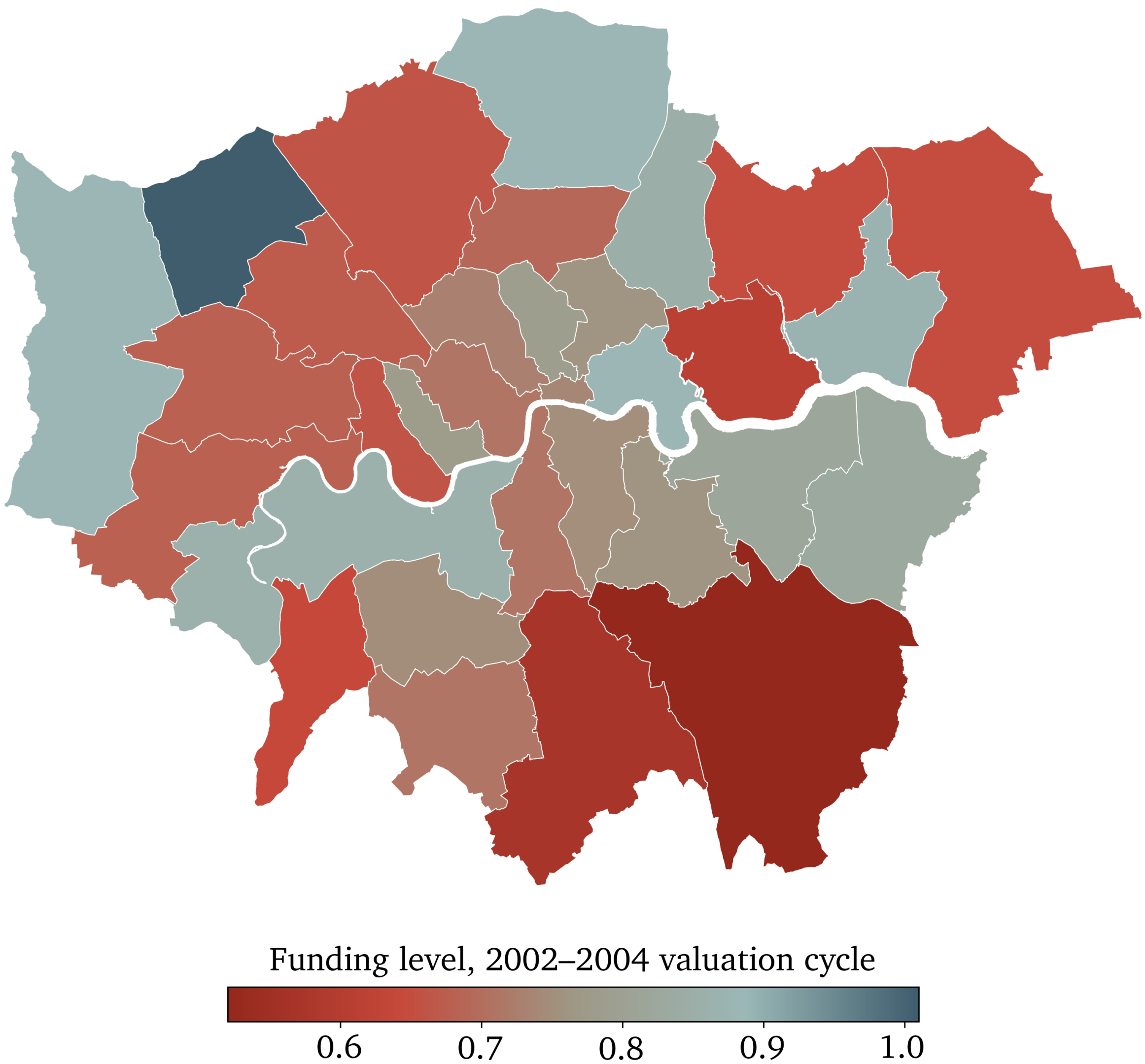


Figure F.6: Distribution of funding levels in London.

The figure shows the distribution of funding levels across local government pension schemes (LGPS) in London for the 2002 to 2004 valuation cycle, which concluded in March 2004. If multiple valuations are available, the latest valuation has been used in the figure. Darker areas reflect lower funding levels. A funding level of less than one indicates that the LGPS was underfunded as defined under the SFO. A map of the U.K. can be found in the main text.

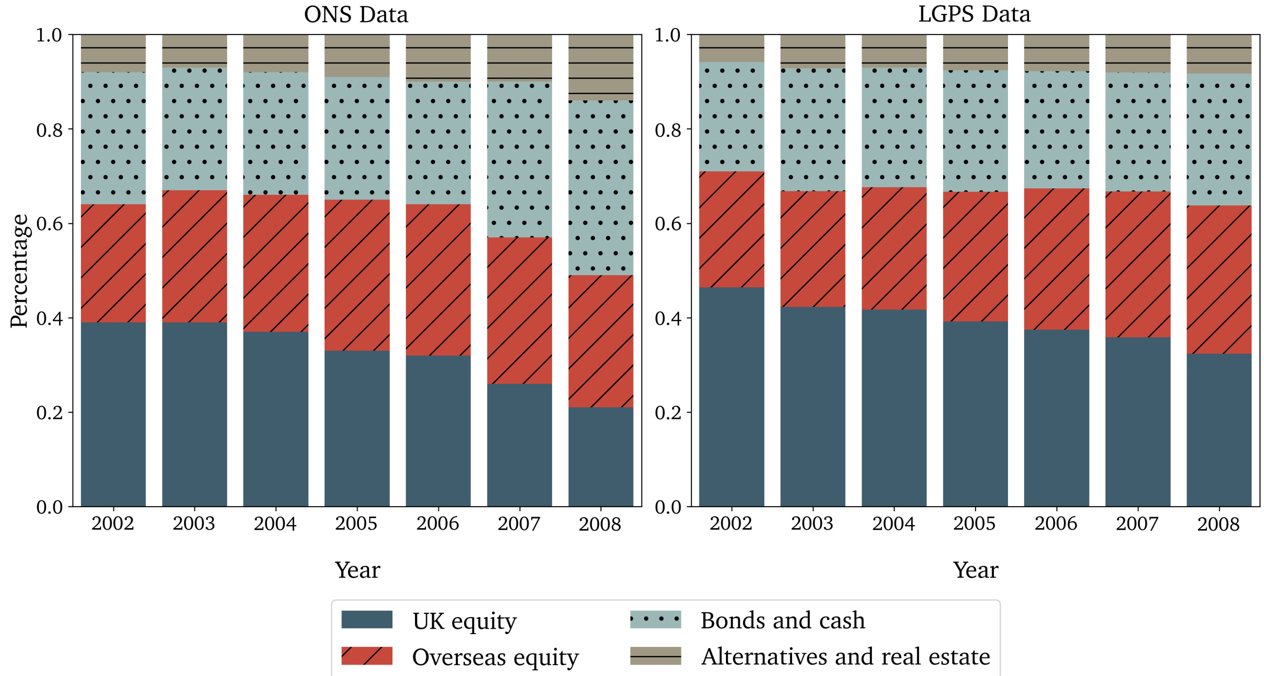


Figure F.7: Representativeness of asset allocation data

This graph shows the asset allocation of an average (size-weighted) pension scheme in the Office of National Statistics' (ONS) MQ-5 survey (left) and in my local government pension scheme (LGPS) data.

F.3 Representativeness

One might be concerned about the representativeness of the sample of local government pension schemes compared to other defined-benefit or defined-contribution pension schemes in the United Kingdom. The Office of National Statistics' (ONS) survey of pension funds, a repeated industry cross-section, can be used to assess the representativeness of LGPS' portfolio allocation for the wider industry. Figure F.7 shows the portfolio shares of the average LGPS (right) and the average scheme in the ONS data (left). On average LGPS, hold a slightly larger fraction of their portfolio in equity and a smaller fraction in bonds than the average scheme. The trends following the pensions reform are similar: Both LGPS and other schemes decrease their portfolio holdings of U.K. equities by around 12 percentage points, if anything the drop is slightly more pronounced for other schemes.

F.3.1 Portfolio concentration

Pension fund portfolios are relatively concentrated with little variation between funds. Table F.2 shows summary statistics on the make-up of pension fund portfolios. I report the average number of stocks held, the standard deviation, the HHI, the standard deviation of

Table F.2: Portfolio concentration

year	2002	2003	2004	2005	2006
$\mu(N)$	163.8	159.2	149.8	142.1	139.4
$\sigma(N)$	65.4	63.2	58.5	55.8	54.2
$\mu(HHI)$	0.1	0.1	0.1	0.1	0.1
$\sigma(HHI)$	0.018	0.018	0.018	0.020	0.020
μ(Cosine)	0.8	0.8	0.8	0.8	0.8
σ(Cosine)	0.3	0.3	0.3	0.3	0.3

This table shows summary statistics on pension schemes' portfolio concentration. $\mu(\cdot)$ and $\sigma(\cdot)$ denote the mean and standard deviation, respectively. The variables are the number of stocks N, the HHI, and the cosine similarity defined in equation F.1.

the HHI across funds, and the cosine similarity between portfolios for the years 2002 to 2006. The average number of stocks held is 164 with standard deviation 65. The portfolio concentration is very low with an HHI of 0.06 and a standard deviation of 0.01. The cosine similarity, defined as:

$$\text{Cosine Similarity}_{f,f'} = \frac{\boldsymbol{\alpha}_f \cdot \boldsymbol{\alpha}_{f'}}{\|\boldsymbol{\alpha}_f\| \, \|\boldsymbol{\alpha}_{f'}\|} = \frac{\sum_{i=1}^{N} \alpha_{f,i} \, \alpha_{f',i}}{\sqrt{\sum_{i=1}^{N} \alpha_{f,i}^2} \sqrt{\sum_{i=1}^{N} \alpha_{f',i}^2}} \tag{F.1}$$

measures the pair-wise similarity between the portfolio vectors α_f and $\alpha_{f'}$ of any two funds f and f' for all funds $1, \ldots, F$ in the sample. A value of zero indicates no overlap between two portfolios a value of 1 indicates identical portfolios. The similarity between portfolios is very high at 0.8 with standard deviation 0.3. There are no significant changes in concentration over time.

F.3.2 Shift-share instrument

This Appendix contains summary statistics for the shift-share instrument used in the main specification in Section 4.1.

Shares. Identification in my setting comes from the shocks rather than the shares. As discussed in Borusyak et al. (2025) and Aghion et al. (2022, p.29), the effective number of shocks in this research design can be quantified by estimating the inverse Herfindahl-Hirschman index (HHI) of the shares $s_{i,f,2002}$. When a few pension funds hold large fractions of individual stocks, the effective sample size is small and the shift-share instrument will not

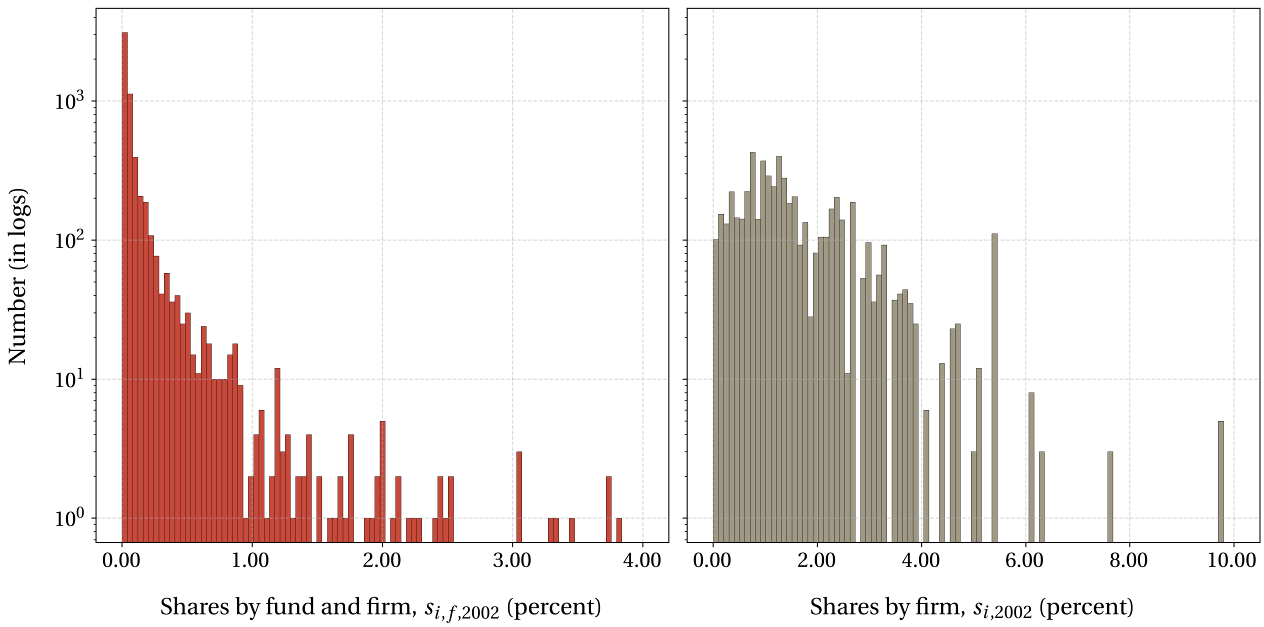


Figure F.8: Distribution of shares.

be a consistent estimator. In my application, the inverse HHI of the shares 153, indicating that the effective sample size is large.

Figure F.8 plots the distribution of shares. The left panel contains a histogram of the shares across funds and firms, $s_{i,f,2002}$. The right panel shows the shares at the firm level, $s_{f,2002}$. A small number of outliers with shares large than five percent have been dropped from the plot for readability.

Shifts. The main specification defines the shift as the percentage change in pension fund equity holdings between the financial years 2003 and 2006. The cross-sectional distribution of these shifts can be found in Figure F.4.

F.4 Details on investment mandates

To illustrate the variation in mandates within and between funds, and the importance of benchmarking, this Appendix collates a few excerpts from LGPS annual reports.

Variation in mandates. Of the 98 pension schemes in the sample, 92 delegate asset management to external managers. As LGPS are public pension schemes, their investment mandates are set by local council pension committees or boards of trustees in three-year cycles.

Mandates can either be active, that is, aiming to outperform a benchmark, or passive, that is, aiming to track one. Most pension funds split their equity allocation between an active and a passive manager, although some funds do not appoint passive managers at all.

A typical active mandate requires an asset manager to match or outperform a benchmark index or peer group by some fixed percentage return. For example, fund trustees often specify that the manager should aim to outperform the average return on the portfolio of LGPS by two or three percentage points over a three year period. To illustrate the importance of mandates and benchmarking, Appendix F.4 contains an excerpt from an annual report detailing an investment mandate that Avon County Council has set for its asset managers.

In addition to return targets, some pension funds pursue secondary objectives. As these are local pension schemes, trustees often require asset managers to invest a fraction of assets in local businesses or projects tied to the local economy. Some LGPS also have a preference for impact or sustainable investments and therefore allocate some of their assets to specialist funds. See, for example, Figure F.3 in Appendix F.1. Figure F.9 shows the details of an investment mandate set by Avon County Council for its three asset managers *Barclays Global Investors* (BGI), *Gartmore Investment Management*, and *Merril Lynch Investment Managers* (MLIM) for the financial year 2001 to 2002. In 2001, Avon Pension Fund held around £1.5 billion of net assets. The fund did not manage any assets in-house. Its funding ratio per the last valuation was 99.4 percent.

As the figure illustrates, two asset managers, BGI and *Gartmore*, are mandated to track the asset allocation of the average LGPS but simultaneously given discretion to determine the asset allocation within their mandate, whereas MLIM is tasked to outperform the average LGPS by 1 percent per year.

Figure F.10 contains the details of another local government pension scheme, *Durham County Council*'s pension fund. The left panel shows the investment mandate handed to *Baring Asset Management* and *Morely Fund Management*, the pension fund's active asset managers, for the 2001 to 2002 financial year. This mandate requires the investment manager to outperform the CAPS total fund median return over a rolling period by 0.5 percent, but does not specify any mandate to replicate the asset allocation of a peer group. Different to *Avon Pension Fund*'s mandate, *Durham* also imposes lower bound on returns, which should not fall further than 1 percent below the benchmark.

The right panel in F.10 shows the investment mandate for Durham's passive manager *Legal and General Investment Management* who are asked to track a series of benchmark indices, such as the *FSTE All-Share Index*.


AVON PENSION FUND ANNUAL REPORT 2001-2002

Investment Commentary

Investment Management Arrangements

For the majority of the financial year 2001/2002, the investment management arrangements were those which have been in place since 1997. However, following a review by the Pensions Committee in December 2000, a new investment management structure was introduced with effect from 14 March 2002. Prior to the change the Fund's investment managers were Barclays Global Investors (BGI), Gartmore Investment Management (Gartmore) and Merrill Lynch Investment Managers (MLIM).

The mandates of these three managers were as follows:-

Barclays Global Investors (BGI) – To replicate as far as possible the asset mix of the average local authority fund and to manage the individual assets on an indexed basis with a view to achieving market returns.

Gartmore Investment Management – As in the case of BGI, to replicate as far as possible the asset mix of the average local authority fund and to manage the individual assets on an indexed basis with a view to achieving market returns.

(Gartmore's mandate was amended on a temporary basis with effect from 1 November 2000 pending implementation of the new investment management structure. Their original performance objective was to outperform the average local authority fund by 0.5% per annum over a rolling three year period by varying the asset mix. The mandate was amended because the portfolio underperformed the average fund).

Merrill Lynch Investment Managers (MLIM) – To vary the stock selection and asset mix of the portfolio with a view to outperforming the average local authority fund by 1% per annum over a rolling three year period.

The Fund's custodian is HSBC Global Investor Services. The custodian is responsible for the safekeeping of the Fund's assets, transaction settlement and income collection. In addition they provide a range of support services, including investment accounting and reporting.

Following an earlier review of investment strategy undertaken by the Fund's actuary, the Pensions Committee decided at its meeting on 10 December 1999 that the property portfolio should be sold. At that date approximately 3% of the Fund was held in property. In order to maximise the sale proceeds a period of three years was allowed for completion of the disposal programme. In the event, the greater part of the property portfolio was sold during the financial year 2001/2002. By 31 March 2002 unsold property amounted to less than 0.5% of the Fund.

Figure F.9: An annual report with detailed asset manager mandate.

Variation over time. Trustees periodically review investment mandates and may revise them in response to regulatory or political changes. Any updates to a mandate are communicated to members through the annual report. Figure F.9 contains an example of *Avon* pension fund amending the mandate of its active asset manager, *Gartmore*.

PERFORMANCE OBJECTIVES

13. The performance objectives of the fund managers are as follows:

(a) **Balanced Fund Managers**

Baring Asset Management and Morley Fund Management

(i) **Long-term objective**: to achieve returns of 0.5% per annum above the CAPS Total Fund (including property) Median, over rolling three year periods.

(ii) **Short-term objective**: returns should not be worse than 1.0% per annum below the CAPS Total Fund (including property) Median over rolling twelve month periods.

(b) **Consensus Manager**

Legal and General Investment Management

The performance objective is to track the relevant indices for each asset class and market, as follows:

Asset Class	Index
UK Equities	FTSE All-Share Index
North American Equities	FTSE North America Index (in Sterling)
Japanese Equities	FTSE Japan Index (in Sterling)
European Equities	FTSE Europe (ex UK) (in Sterling)
Pacific Equities	FTSE All World Asia Pacific (ex-Japan) Developed Index (in Sterling)
UK Gilts	FTSE-A Government (All Stocks) Index
Index-Linked Gilts	FTSE-A Index-Linked (All Stocks) Index
Overseas Bonds	JP Morgan Global (ex UK) Traded Bond Index (in Sterling)

Figure F.10: An annual report with detailed asset manager mandate.

G Appendix – Empirics

G.1 Trends in asset allocation

In this section, I document four *stylised facts* about the asset allocation of pension funds, which motivate my firm-level analysis: First, the pension reforms of the 1990s and early 2000s precipitate a long-run decline in the equity portfolio share on pension funds' balance sheets. Second, until the mid 2000s, this decline was driven by valuation effects on U.K. assets rather than active sales of stocks. Net quantities held by pension funds remained stable. Third, pension funds started to actively sell equities only with the announcement and implementation of the Pension Act 2004. And fourth, sell-offs were concentrated among those pension funds with large accounting deficits prior to the implementation of the reform.

G.1.1 Portfolio composition

Figure G.1 shows the portfolio composition for an average DB pension fund in the U.K. from 1962 to 2023. Until the early 1980s, pension schemes typically targeted an equity allocation of around 50 percent with the remainder held in gilts and property trusts.

Following the liberalisation of the 1980s, pension funds began to diversify internationally. Equity holdings reached a peak of almost 75 percent during the 1990s and remained relatively stable at around 60 percent until the early 2000s when falling equity prices after the end of the dotcom bubble brought down the equity portfolio shares. With the introduction of the Pensions Act 2004, as indicated by the dashed black line, the equity portfolio share started to decline and hit around 50 percent prior to the Global Financial Crisis (GFC). Within equity, the share of U.K. investment already started to decline in the late 1990s. The announcement and implementation of the Pensions Act 2004 accelerated this trend.

G.1.2 Prices versus quantities

Of course, the decline in the equity portfolio share could be driven by either active sales or by valuation effects of domestic stocks. To separate price from quantity effects, I run a decomposition in Appendix G.1.2. The analysis confirms that the reduction in pension funds' equity portfolio share prior to the announcement of the 2004 reform was driven by relative valuation effects but pension funds remained net buyers of U.K. equities. Post announcement, however, they became net sellers of equities with valuation effects even softening the decline in the equity portfolio share.

To disentangle changes in relative prices of U.K. equities compared to overseas equities from active sales of U.K. stocks, I introduce the following decomposition. Let E_t denote

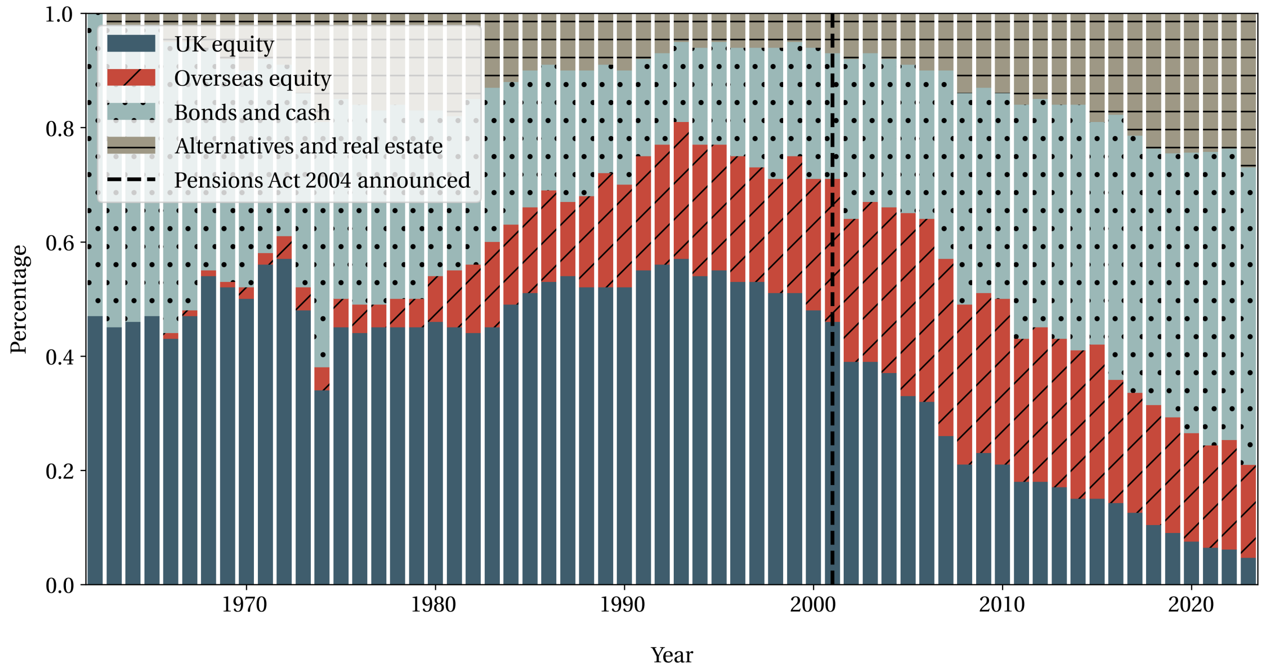


Figure G.1: Long-term trends in pension fund asset allocation.
This figure shows the long-term evolution of an average defined-benefit pension fund. The data in this figure is from the Office of National Statistics' (ONS) Financial Survey of Pension Schemes (FSPS), a repeated cross-section of 360 pension schemes in the U.K.. Averages are seize-weighted across pension funds to reflect average holdings across funds.

total value of holdings at time t consisting of quantities Q_t at prices P_t. The change in total holdings between years t and $t+1$ consists of a price component, a quantity component, and an interaction term:

$$E_{t+1} - E_t = \underbrace{Q_t\left(P_{t+1} - P_t\right)}_{\text{price component}} + \underbrace{P_t\left(Q_{t+1} - Q_t\right)}_{\text{quantity component}} + \underbrace{\left(P_{t+1} - P_t\right)\left(Q_{t+1} - Q_t\right)}_{\text{interaction term}}. \tag{G.1}$$

The quantity component reflects the adjustment to holdings due to sales or purchases of stocks, while the price component captures changes in holdings due to price changes. Following the same logic, I define the change in any variable X_t between any two years t and $t+T$ as $\Delta X_{t+T} \equiv X_{t+T} - X_t$, where $X \in \{E, P, Q\}$. Chaining up these changes over time and cancelling terms, $\Delta E_{t+T} = (E_{t+T} - E_{t+T-1}) - (\dots) - (E_{t+1} - E_t)$, we obtain the following expression for the total change in equity holdings over the horizon T:

$$\underbrace{\Delta E_{t+T}}_{\text{total change}} = \underbrace{\sum_{j=0}^{T} Q_{t+j}\Delta P_{t+j+1}}_{\text{price component}} + \underbrace{\sum_{j=0}^{T} P_{t+j}\Delta Q_{t+j+1}}_{\text{quantity component}} + \underbrace{\sum_{j=0}^{T} \Delta Q_{t+j+1}\Delta P_{t+j+1}}_{\text{interaction term}}. \tag{G.2}$$

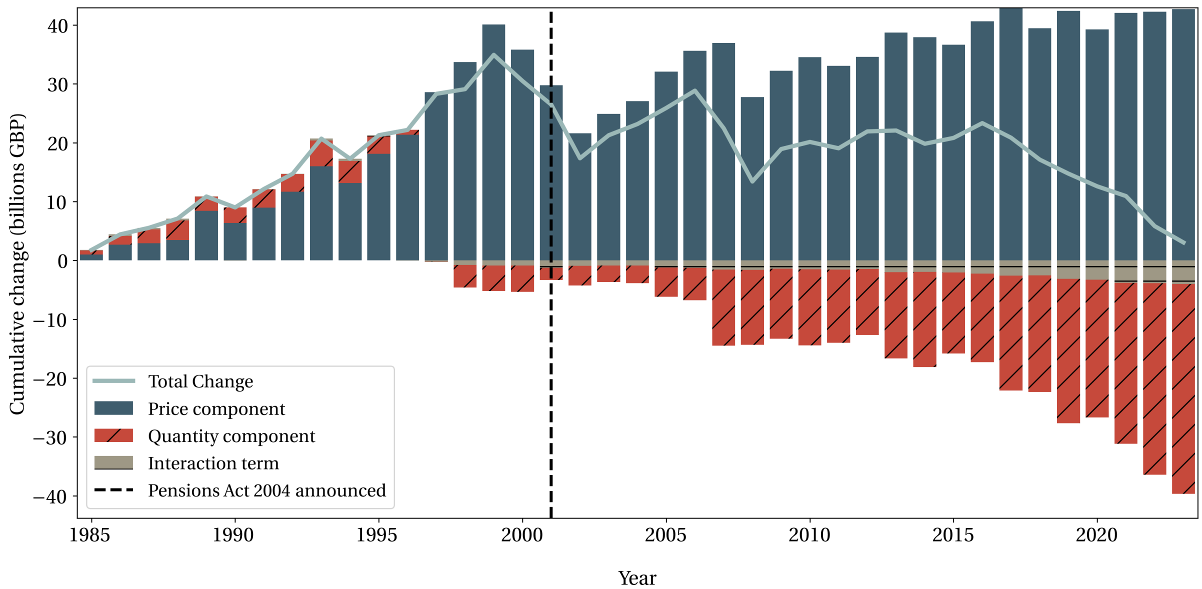


Figure G.2: Changes in stock holdings due to discretionary and price components.
This figure shows the cumulative changes in the equity portfolio share driven by prices, quantities, and their interaction corresponding to the decomposition in equation (G.2).

The decomposition in equation (G.2) consists of three parts. The first term captures the cumulative effect of stock price changes over time, holding quantities constant at their previous level. The second term reflects changes in the quantity of stocks held, holding quantities constant at their previous level. The third term is an interaction component that accounts for the combined effect of simultaneous changes in both prices and quantities. The price component can be thought of as reflecting the passive revaluation of existing holdings, while the quantity component reflects pension funds' active decisions to buy or sell stocks.

Figure G.2 illustrates this decomposition using the same holdings data used in the previous section. As in Figure G.1, the dashed black line indicates the announcement of the Pensions Act 2004. The solid teal line is the total change in equity holdings relative to the base year of 1985, blue bars correspond to price effects, red bars to quantity effects, and beige bars to the interaction component between the two.

Until the late 1990s, pension funds were net buyers of U.K. stocks with small-volume sales occurring during the financial years 1998 to 2000. Figure G.2 also illustrates that the Pension Act 1995 had relatively little if any effect on equity holdings. With the announcement and implementation of the Pensions Act 2004, pension schemes started to sell larger quantities of U.K. equity. This trend particularly accelerated after the financial crisis.

G.2 Aggregate flows for insurance companies and pension funds

This Appendix contains further plots illustrating the impact of the pensions reform. To show that equity sales limited to pension funds after the reform, Figure G.3 plots quarterly net flows for pension funds and insurance companies by asset class. Figure G.4 shows the cumulative flows.

As panel (1) illustrates, pension funds were net buyers of equities until early 2003 and only started to sell around the passage of the Pensions Act 2004. Insurance companies, in contrast, barely changed their equity holdings between 2002 and 2007. See Panel (2).

G.3 Fund-level results

This Appendix contains a series of results related to the cross-sectional variation at the fund level.

G.3.1 Funding regressions

This Appendix discusses the result of the main regression in (3.2). Column (1) of Table G.1 reports the coefficient of interest. The regression suggests that a one percentage point lower funding level in 2002 corresponds to a 0.2 percentage point additional decrease in the equity portfolio share for the period from 2003 to 2007.

To ensure that the effects are driven by quantities rather than prices, I rerun the analysis in Figure 3.3 with holdings normalised to 2003 prices. As these regressions are run on aggregate data, I use the chained price index from Appendix G.1.2 to deflate equity valuations to 2003 levels. The results of this adjusted quantity regression are in column (2). As with the raw equity valuations, the regression results suggest that pension funds with a lower funding level (a larger deficit) in 2002, sold larger quantities of equities in the period from 2003 to 2007. Figure G.5 plots the coefficients for the normalised regression.

G.3.2 Equity exposure regressions

This Appendix contains the regression output for the equity exposure regression (4.3) in Section 4.3. I report three variations of the same regression with no fixed effects, year, and year and fund fixed effects. The results suggest that a higher equity portfolio share is associated with a lower funding level. Controlling for the portfolio share, past returns do not predict pension schemes' funding levels.

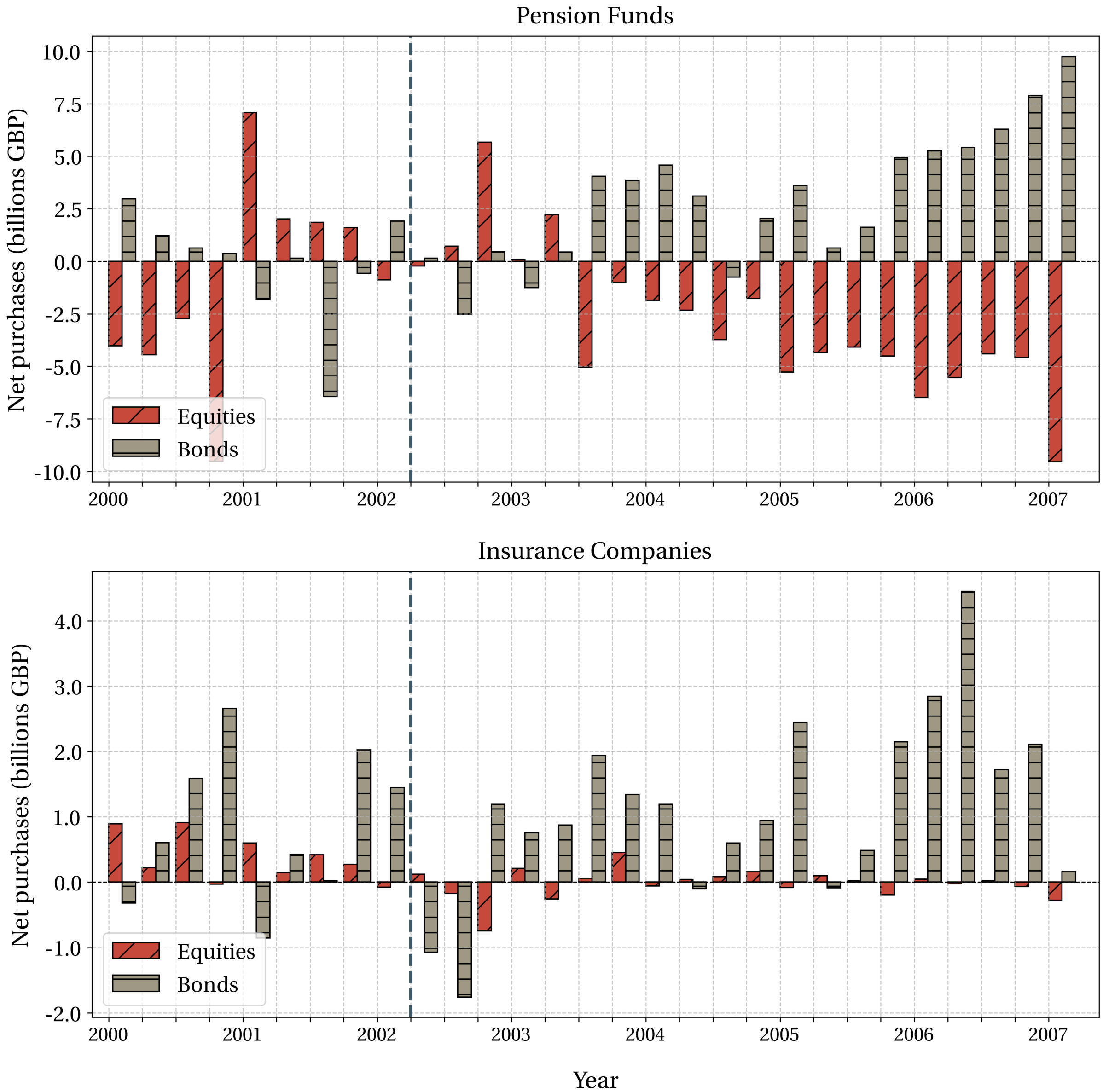


Figure G.3: Net purchases by pension funds and insurance companies.

The top (bottom) panel shows net purchases of bonds and equities for pension funds (insurance companies) from 2000-Q1 to 2007-Q1. The dashed line indicates the announcement of the Pensions Act 2004. The data come from the Office of National Statistics' MQ5 survey of pension funds.

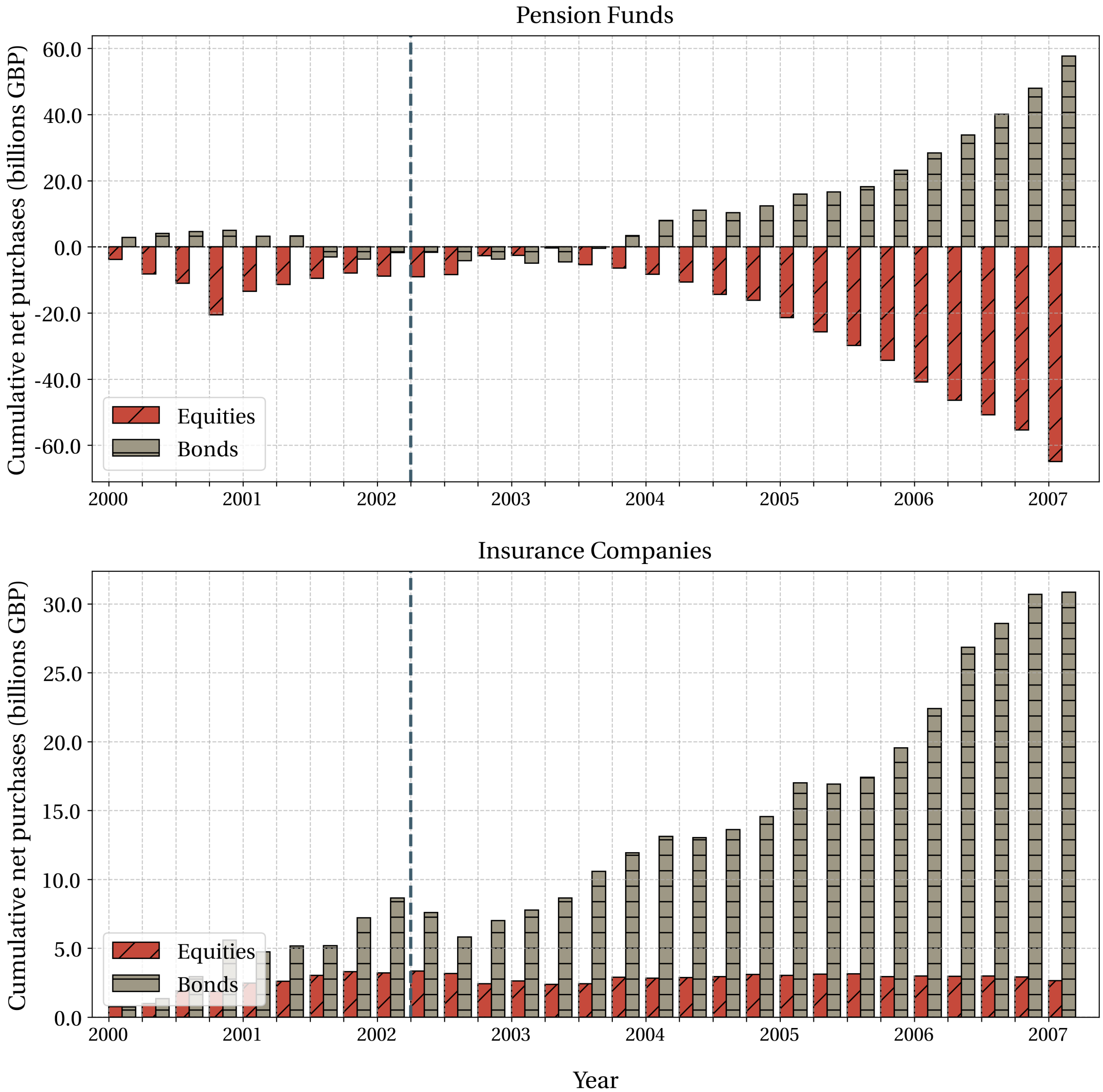


Figure G.4: Cumulative net purchases by pension funds and insurance companies.

The top (bottom) panel shows cumulative net purchases of bonds and equities for pension funds (insurance companies) from 2000-Q1 to 2007-Q1. The dashed line indicates the announcement of the Pensions Act 2004. The data come from the Office of National Statistics' MQ5 survey of pension funds.

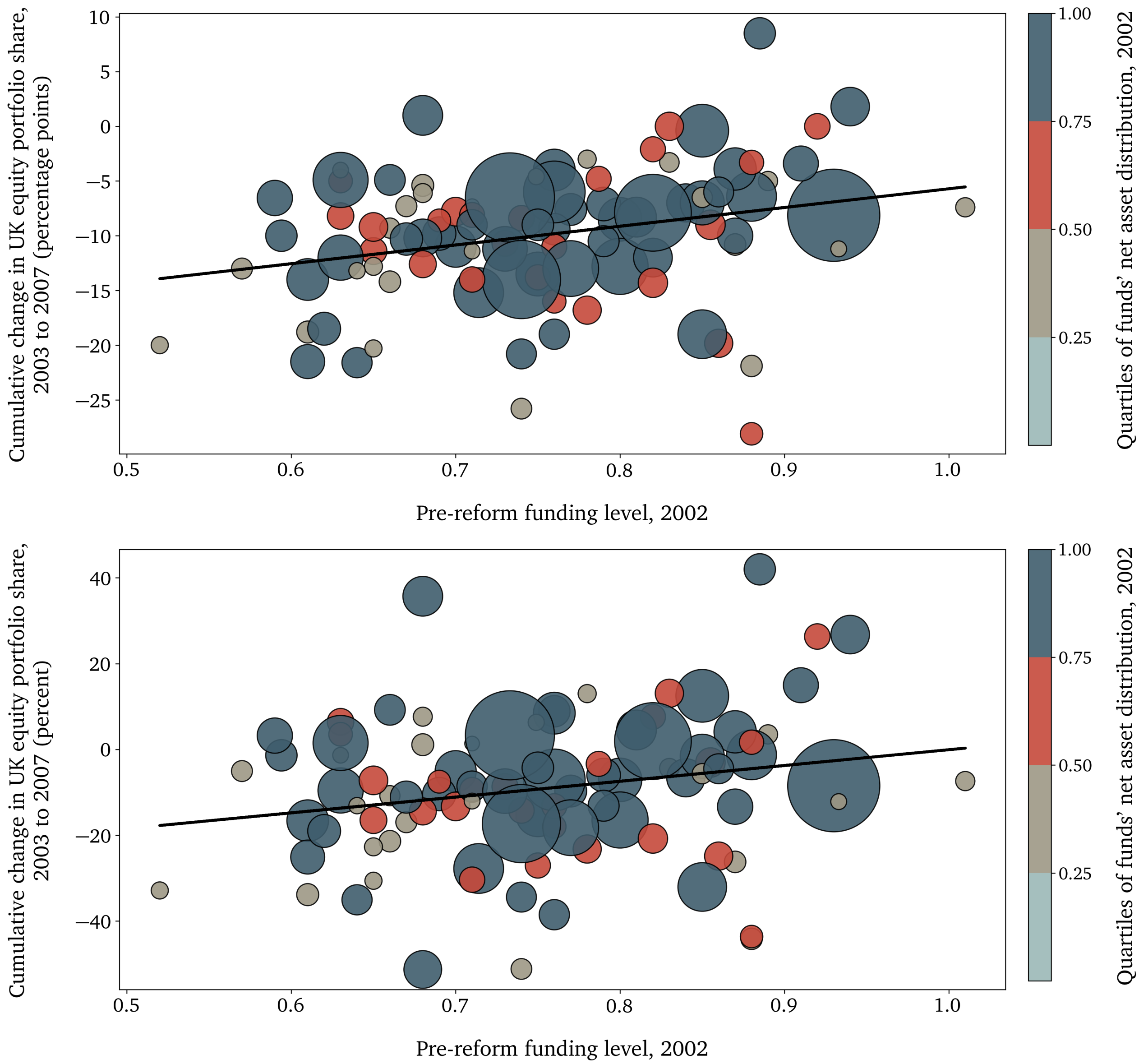


Figure G.5: Change in price-adjusted equity portfolio share.

Top panel: Base specification; Bottom panel: normalised values. Bubble sizes capture fund net assets in 2003. Colours correspond to quartiles in the net asset distribution of funds.

Table G.1: Funding level and change in equity portfolio share

	(1)	(2)
	Δ (Equity Portfolio Share)$_{i,2007-2003}$	Δ (Adj. Equity Portfolio Share)$_{i,2007-2003}$
(Funding Level)$_{i,2002}$	0.1795***	0.4671*
	(0.0643)	(0.267)
Constant	-0.2281***	-0.4068**
	(0.0048)	(0.199)
Observations	98	98
R-squared	0.099	0.061

Robust standard errors in parentheses, $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$

G.4 Firm-level results

This Appendix contains further empirical results on stock returns complementing the firm-level analysis in Section 4.

G.4.1 Returns

Using daily returns data from COMPUSTAT CAPITAL IQ, I construct cumulative *gross* annual returns $R_{i,2002+h}$ for all public firms in the sample. I then run a regression mirroring (4.2) on the cumulative change in gross returns based on firms' exposure to pension fund capital. Formally, I run:

$$\ln\left(\frac{R_{i,2002+h}}{R_{i,2002+h-1}}\right) - \ln\left(\frac{R_{i,2002}}{R_{i,2001}}\right) \\ = \alpha_h + \beta_h Z_{i,2002} + \gamma_h' X_{i,2002} + \delta_{i,h} \sum_{f=1}^{F_{i,2002}} s_{i,f,2002} + \varepsilon_{i,h}. \tag{G.3}$$

The data has been winsorised at the 5^{th} and 95^{th} percentiles, and standard errors are clustered at the firm level. I control for the changes in book to market value and market capitalisation prior to the reform, cash-on-hand relative to assets, the share of intangible assets, research and investment intensities, and firm size proxied by total employment. Figure G.6 plots the results.

After the announcement of the reform, stock returns fall, first gradually, and then faster once pension funds' equity sales start to ramp up in 2004. I estimate that firms that saw a one percentage point larger decrease in pension fund shareholding, post around 0.05 percentage points lower annual gross returns in 2004 relative to the baseline year 2002.

Table G.2: Equity exposure regression

	(1)	(2)	(3)
	Funding level	Funding level	Funding level
RoA	-0.00005***	-0.00001	-0.00001
	(0.00001)	(0.00001)	(0.00001)
Bond Share	-0.12696	-0.19010*	-0.09166
	(0.08348)	(0.07561)	(0.11179)
UK Equity Share	-0.16038*	-0.23401**	-0.19898*
	(0.07642)	(0.07826)	(0.09309)
Assets	0.00001***	0.00001***	0.00000
	(0.00000)	(0.00000)	(0.00001)
Membership	0.28929***	0.25701**	-0.21632
	(0.08480)	(0.07955)	(0.18056)
Constant	0.73052***	0.78644***	0.99960***
	(0.05927)	(0.06139)	(0.10255)
Year FE		✓	✓
Fund FE			✓
Observations	426	426	426

Standard errors in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

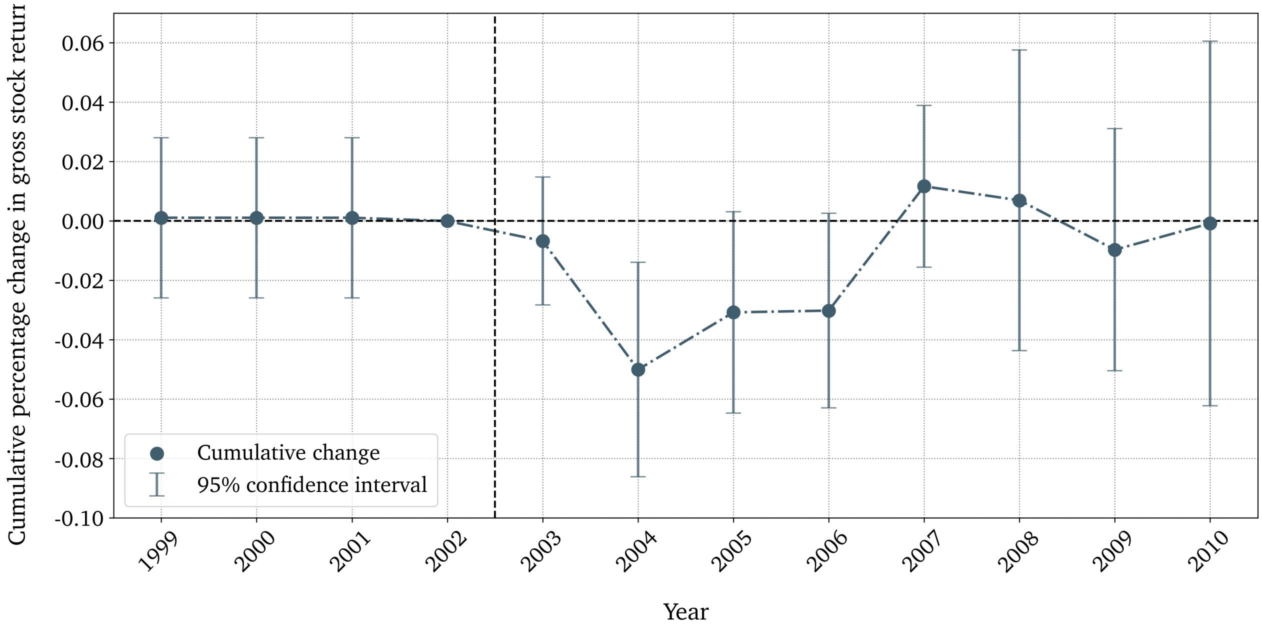


Figure G.6: Effect on stock returns.

The figure shows the cumulative effect of a one percentage point differential reduction in pension fund equity ownership at horizon h as captured by β_h in equation (4.2). The dependent variable is the cumulative annual stock return.

This effect persists until the sell-offs come to a halt in 2006 and washes out thereafter.

G.4.2 Leverage

Next, I evaluate the impact on firms' capital structure. I measure leverage as the ratio of long-term debt over the sum of equity and long-term debt. I then run a regression of the form (4.2) on the cumulative change in leverage based on firms' exposure to pension fund capital.

The top panel of Figure G.7 shows the cumulative effect of a one-percentage point reduction in pension fund investment on firms' leverage. An additional one-percentage point decrease in the share of pension fund investment increases leverage by about one percent after five years.

G.4.3 Asset maturity

Finally, I analyse how pension investment affects the composition and maturity of firm investment. Following Stohs and Mauer (1996) and in particular the methodology set out in

Hubert de Fraisse (2024), I define a firm's asset maturity as:

$$AM_{i,t} = \frac{CA_{i,t}}{CA_{i,t} + NetPPE_{i,t}} \cdot 1 + \frac{NetPPE_{i,t}}{CA_{i,t} + NetPPE_{i,t}} \cdot \frac{1}{\delta_{i,t}}, \tag{G.4}$$

where $CA_{i,h}$ are firm i's current assets; $NetPPE_{i,h}$ is net property plant and equipment; and $\delta_{i,t}$ is the firm's depreciation rate. The idea (G.4) is to proxy for a firm's investment horizon via the composition of its assets, or more precisely their depreciation rate. Current assets are used for production and therefore fully depreciated in a given financial year. Fixed assets, such as net PPE, can be used over a longer period, which is captured by their respective depreciation rates. Intuitively, the geometric depreciation weights $1/\delta_{it}$ assign high weights to assets with low depreciation rates which will be used to generate cash flow in the far future.[27]

Based on (G.4), I run the reduced-form regression (4.2) using asset maturity as the dependent variable. The results in Figure G.7 suggest that pension investment has a persistent effect on firms' asset composition. On average, firms more exposed to pension fund investment see a forwards shift in their asset composition. A one percentage point differential reduction in pension fund ownership is associated with a 0.4 percent decrease in asset maturity as defined in (G.4). This effect is highly persistent and still visible after eight to ten years. In line with my results for capital investment and R&D, I interpret these findings as corroboration of my hypothesis that firms react to the withdrawal of pension funds from equity markets by cutting down on long-term investment and focusing on the short term.

G.5 Robustness

This section presents the results of various alternative specifications and robustness checks complementing the main empirical results in Section 4. To confirm the robustness of the main specification in Section 4, I rerun my main regression for series of alternative set-ups. In Section G.5.1 I swap out the base year 2002 against 2003. In Section G.5.2 I use an asset-under-management weighted shifter, where I weight sales by pension schemes' assets under management. In Section G.5.3 I construct a leave-one-out instrument that excludes fund f's sale of firm i's equity in the firm-specific shifter. Finally, in Section G.5.4 I leverage an alternative instrument based on pension schemes' membership structure prior to the reform.

[27] The results are robust to using cash flow-based measures of asset maturity (Goncalves, 2021).

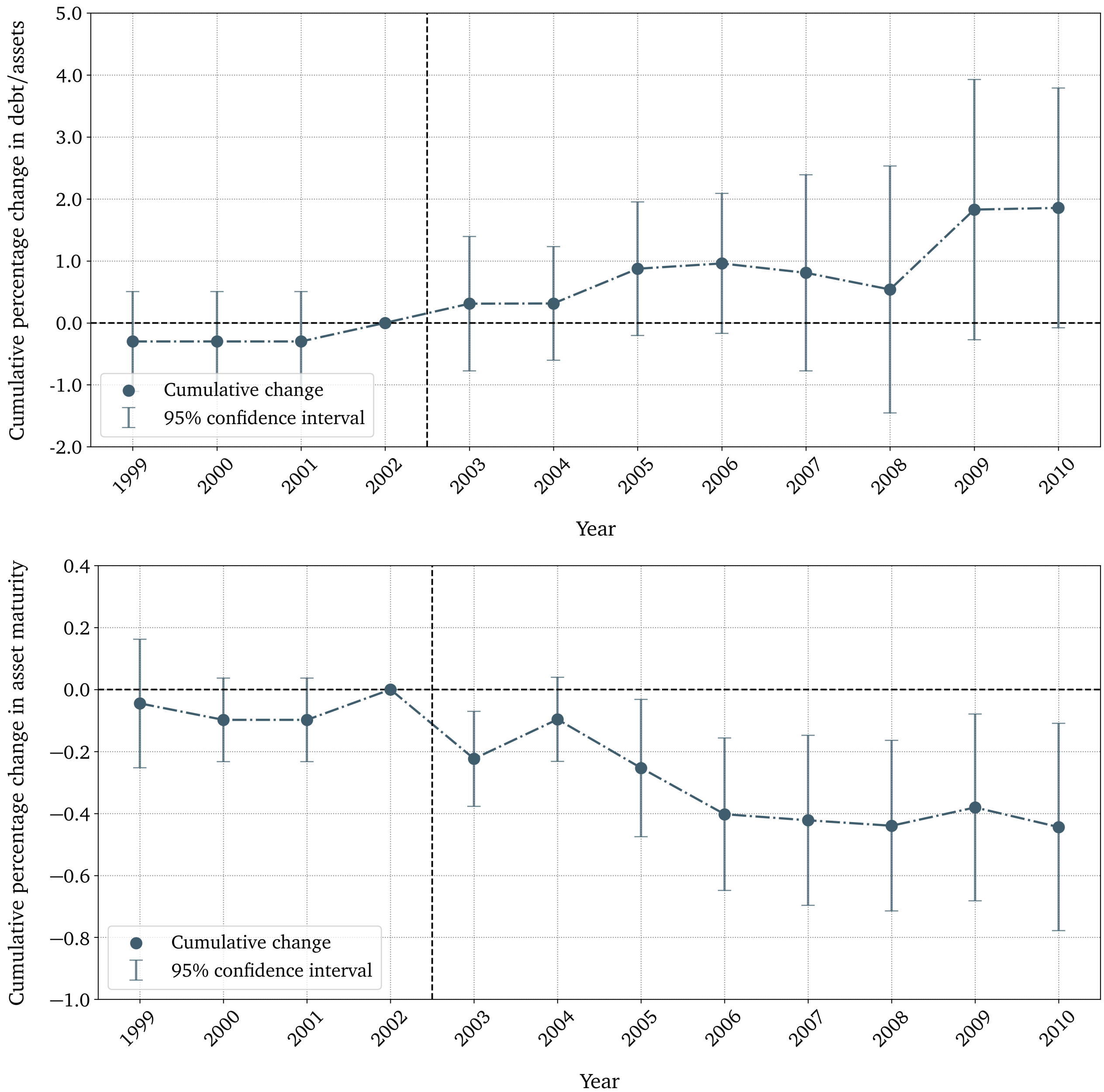


Figure G.7: Effect on leverage and asset maturity.

The top panel of the figure shows the cumulative effect of a one percentage point differential reduction in pension fund equity ownership at horizon h captured by β_h in equation (4.2). The dependent variable is leverage as defined in the text. The bottom panel of the figure shows the cumulative effect of a one percentage point differential reduction in pension fund equity ownership at horizon h captured by β_h in equation (4.2). The dependent variable is asset maturity defined in equation (G.4).

G.5.1 Alternative base year

One might be concerned that the results in the main text are driven by shocks that occurred between the base period of 2002 and the implementation of the reform in 2004 and which were correlated with firms' exposure to pension fund equity prior to the reform.

To confirm the robustness of my results to this threat to identification, I rerun the main regressions in Section 4.1 using the alternative base year 2003 to construct the equity shares. Formally, let $s_{i,f,t}$ denote pension funds f's share of equity capital in firm i at time t for funds $f = 1, \dots, F$ and let $M_{f,t}$ denote the total equity holdings of fund f on its balance sheet at time t. I then construct the shift-share instrument as follows:

$$Z_{i,2003} = \sum_{f=1}^{F} \underbrace{s_{i,f,2003}}_{\text{2003-share}} \cdot \underbrace{(\ln M_{f,2003} - \ln M_{f,2007})}_{\text{2003-shift}}, \tag{G.5}$$

where I use the shift until 2007 as the baseline shock to retain the three-year structure of the instrument. I then run the reduced form (4.2) using the same controls as in the baseline and clustering standard errors at the firm level.

The results of my regression using this alternative specification support the baseline results with pre-treatment year 2002. The tables and figures are collated in the supplementary appendix available upon request.

G.5.2 Asset-weighted instrument

One might be concerned that the effects of the divestment from equity are related to the behaviour of a few large pension funds or that there is heterogeneity in divestment from equity based on fund size.

To confirm the robustness of my results to this threat to identification, I rerun the main regressions in Section 4.1 with fund weights based on pension schemes' assets under management (AUM) prior to the reform. Formally, let $s_{i,f,t}$ denote pension funds f's share of equity capital in firm i at time t for funds $f = 1, \dots, F$ and let $M_{f,t}$ denote the total equity holdings of fund f on its balance sheet at time t. Moreover, I define the AUM-weights $a_{f,t}$ per fund as:

$$a_{f,t} = \frac{A_{f,t}}{\sum_{f=1}^{F} A_{f,t}}, \tag{G.6}$$

where $A_{f,t}$ are a pension schemes' total investment assets. The baseline period is again 2002, prior to the announcement of the Pensions Bill. Using these weights, I then construct the shift-share instrument as follows:

$$Z_{i,2002}^{AUM} = \sum_{f=1}^{F} \underbrace{s_{i,f,2002}}_{\text{share}} \cdot \underbrace{a_{f,2002} \cdot (\ln M_{f,2003} - \ln M_{f,2006})}_{\text{AUM-weighted-shift}}, \tag{G.7}$$

and rerun the reduced form (4.2) using the same controls as in the baseline and clustering standard errors at the firm level.

The results of my regression using the AUM-weighted instrument support the baseline specification. There is no evidence for heterogeneity based on fund size. The tables and figures are collated in the supplementary appendix available upon request.

G.5.3 Leave-one-out instrument

One might be concerned that the results in the baseline specification are driven by pension funds divesting large amounts from a few large firms. If the sell-off from these firms is large relative to other firms, the regression in (4.2) will be contaminated by a firm's "own shock" and the baseline specification would amount to a regression of a firms' stock price on an object that is highly correlated with its own price.

To confirm the robustness of my results to this threat to identification, I rerun the main regressions in Section 4.1 using a leave-one-out instrument (LOO). Formally, let $s_{i,f,t}$ denote pension funds f's share of equity capital in firm i at time t for funds $f = 1, \ldots, F$ and let $M_{i,f,t}$ denote the total equity holdings of fund f in firm i on its balance sheet at time t. I then construct the shift-share instrument as follows:

$$Z_{i,2002}^{LOO} = \sum_{f=1}^{F} \underbrace{s_{i,f,2002}}_{\text{share}} \cdot \underbrace{\left[\frac{\ln \left(\sum_{j \neq i} M_{j,f,2006} \right)}{\ln \left(\sum_{j \neq i} M_{j,f,2002} \right)} \right]}_{\text{LOO-shift}}, \tag{G.8}$$

where the shifter leaves out the shock to firm i itself. I then rerun the reduced form (4.2) using the same controls as in the baseline and clustering standard errors at the firm level.

The results of my regression using the LOO instrument support the baseline specification. There is no evidence that results are driven by firms' own shock. The graphs and tables are collated in the supplementary appendix available upon request.

G.5.4 Membership instrument

One might be concerned that the funding level itself is endogenous to firms' investment practices. I have already addressed these concerns in Section G.3.2 where I present evidence that suggests that differences in funding levels are driven by equity exposure, but not by differences in allocations within equity. Regardless, this Appendix provides an alternative set-up to the baseline regression (4.2) using an alternative instrument based on firms' membership structure.

The idea behind this instrument is as follows: The funding level $\mathcal{F}_t$ defined in (3.1) depends on the net present value of future pension obligations. How high a scheme's future obligations are depends, in turn, on the ratio of contributors to pensioners. A pension scheme with few active contributors and many pensioners faces higher liabilities while collecting lower contributions. Hence, its funding level should be systematically lower. If the differences in funding levels between pension schemes are indeed driven by their future pension obligations, the membership should be predictive of schemes' divestment from equities in response to the pensions reform. Figure G.5.4 illustrates that this is indeed the case. Using this logic, I define a scheme's age-structure:

$$N_{f,t} = \frac{(\text{Number of Active Contributors})_{f,t}}{(\text{Total Number of Members})_{f,t}}. \tag{G.9}$$

One interpretation of G.9 is that of a dependency ratio, that is, the number of active contributors per retiree or deferred member of the scheme. I then use the membership structure $N_{f,t}$ to construct the following instrument:

$$Z^{MEM}_{i,2002} = \sum_{f=1}^{F} \underbrace{s_{i,f,2002}}_{\text{share}} \cdot \underbrace{(\ln N_{f,2004} - \ln N_{f,2002})}_{\text{MEM-shift}}, \tag{G.10}$$

where I use the pre-reform trends in fund membership structure as an instrument for the funding level. I choose as the baseline period the years 2002 to 2004. The key assumption here is that the changes in membership structure are plausible exogenous to firm performance and affect the divestment from equities only through their impact on funding levels. I include the same control variables as before but do not cluster standard errors. I also control for fund size as Figure G.5.4 suggest that smaller funds tend to have higher dependency ratios.

I then rerun (4.2) using this instrument. The results from this alternative specification using the membership instrument are very similar to the baseline but with considerably less power due to the nature of the instrument. The graphs and tables are collated in the supplementary appendix available upon request.

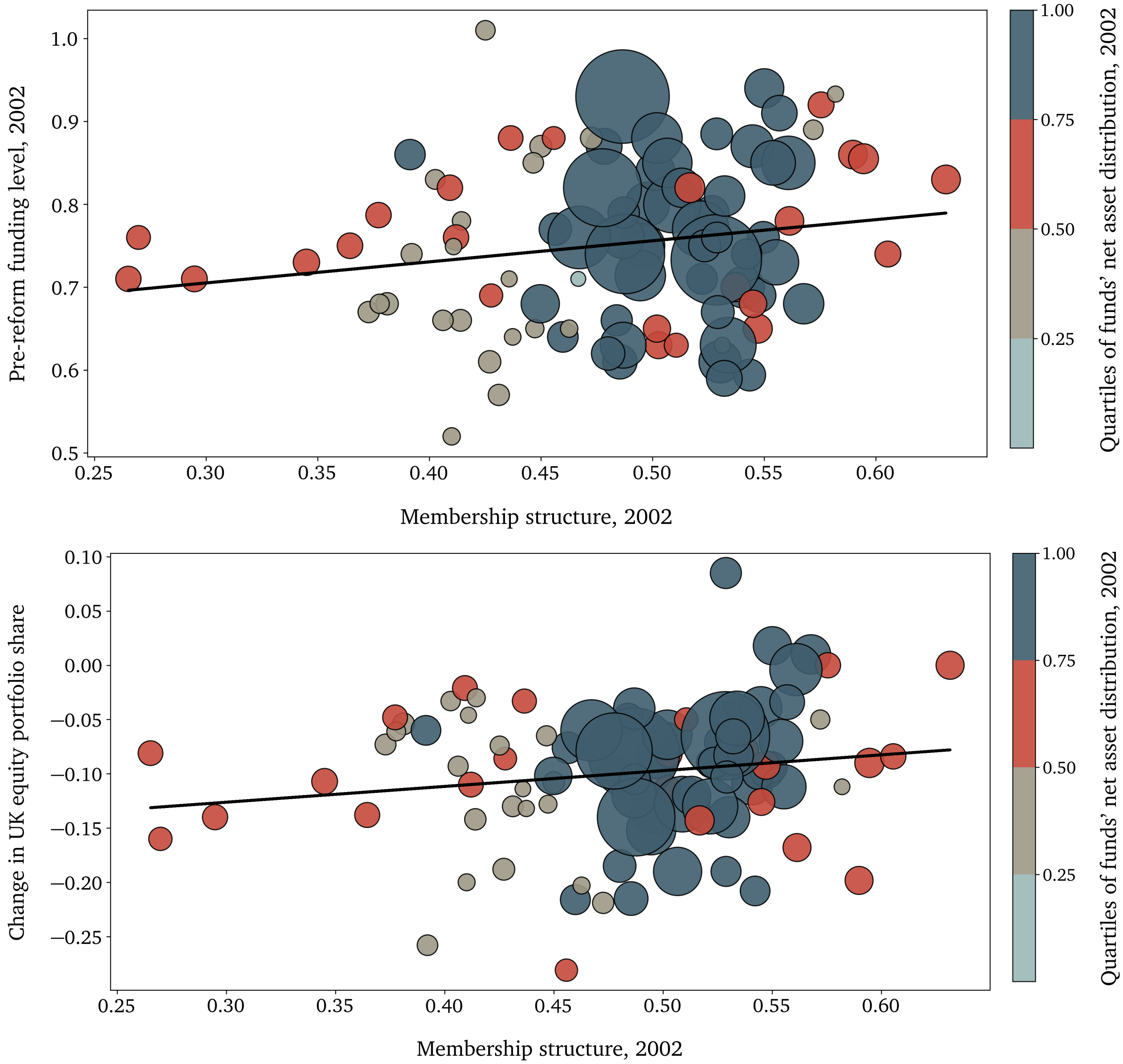


Figure G.8: Pre-reform membership structure, funding level, and post-reform equity sales.

The top panel shows the correlation between schemes' membership structure as defined in (G.9) and their pre-reform funding level, both measured in 2002. The bottom panel shows the correlation between membership structure and the change in the equity portfolio share after the reform from 2003 to 2007. These results are robust to removing outliers with a membership ratio $N_{f,2002} \leq 0.4$ and to seize-weighting schemes by assets.

G.6 List of local government pension schemes

The following table contains a list of all pension funds in the data set as well as the coverage and the data source for each fund's balance sheet data. The data on raw portfolio allocations (UK equity, overseas equity, bonds, other) used for the analysis in Section G.1 are available for all funds.

Table G.3: List of local government pension schemes.

#	LGPS	Source	Coverage	Note
1	Avon	FOI	2000-2023	
2	Barking and Dagenham	FOI	2004-2023	
3	Barnet	FOI	2004-2024	
4	Bedfordshire	FOI	2000-2023	
5	Berkshire	FOI	2000-2023	
6	Bexley	FOI	2004-2024	
7	Brent	FOI	2001-2023	
8	Bromley	FOI	2005-2024	
9	Buckinghamshire	FOI	2005-2023	
10	Cambridgeshire	FOI	2002-2024	
11	Camden	FOI	2002-2024	
12	Cardiff and Vale of Glamorgan	FOI	2005-2024	
13	Cheshire	FOI	2003-2024	
14	City of London Corporation	London Archives	2005-2014	

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#	LGPS	Source	Coverage	Note
15	City of Westminster	FOI	2005-2023	
16	Clwyd	FOI	2005-2023	
17	Cornwall	FOI	2015-2024	
18	Croydon	FOI	2000-2023	
19	Cumbria	FOI	2002-2023	
20	Derbyshire	FOI	2002-2023	
21	Devon	FOI	2002-2023	
22	Dorset	FOI	2002-2023	
23	Dumfries and Galloway	FOI	2002-2023	
24	Durham	FOI	2000-2023	
25	Dyfed	FOI	2000-2023	
26	Ealing	FOI	2002-2024	
27	East Riding	East Riding Archives	1997-2023	
28	East Sussex	FOI	2002-2023	
29	Enfield	FOI	2004-2024	
30	Essex	FOI	2002-2023	
31	Falkirk	FOI	2002-2023	
32	Fife	FOI	2005-2024	
33	Gloucestershire	FOI	2003-2018	

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#	LGPS	Source	Coverage	Note
34	Greater Gwent (Torfaen)	FOI	2001-2017	
35	Greater Manchester	FOI	2001-2023	
36	Greenwich	FOI	2000-2012	
37	Gwynedd	FOI	2004-2023	
38	Hackney	FOI	2003-2022	
39	Hammersmith and Fulham	FOI	2002-2024	
40	Hampshire	Hampshire Archives	2006-2023	
41	Haringey	FOI	2005-2024	
42	Harrow	FOI	2002-2023	
43	Havering	FOI	2005-2024	
44	Hertfordshire	FOI	1999-2023	
45	Highland	FOI	2004-2024	
46	Hillingdon	FOI	2002-2024	
47	Hounslow	FOI	2004-2024	
48	Isle of Wight	FOI	1999-2024	
49	Islington	FOI	2000-2021	
50	Kensington and Chelsea	FOI	2001-2024	
51	Kent	FOI	2007-2023	

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#	LGPS	Source	Coverage	Note
52	Kingston upon Thames	FOI	2004-2024	
53	Lambeth	FOI	2003-2008	
54	Lancashire	FOI	2012-2021	
55	Leicestershire	FOI	2001-2024	
56	Lewisham	FOI	2006-2021	
57	Lincolnshire	FOI	2004-2024	
58	Lothian	FOI	2000-2024	Including Scottish Homes (closed in 2004) and Lothian Bus Fund
59	Merseyside	FOI, Wirral Archives	2001-2024	
60	Merton	FOI	2002-2024	
61	Newham	FOI	2002-2025	
62	Norfolk	FOI	2001-2024	
63	North East Scotland	FOI	2001-2023	
64	North Yorkshire	FOI	2002-2024	
65	Northamptonshire	FOI	2003-2024	
66	Northern Ireland	FOI	2004-2024	
67	Northumberland	FOI	2002-2019	
68	Nottinghamshire	FOI	2002-2009	

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#	LGPS	Source	Coverage	Note
69	Orkney Islands	FOI	2002-2024	
70	Oxfordshire	FOI	2001-2012	
71	Powys	FOI	2002-2023	
72	Redbridge	FOI	2001-2024	
73	Rhondda Cynon Taf	FOI	2000-2024	
74	Richmond upon Thames	FOI	2007-2016	Merged with Wandsworth 2016
75	Scottish Borders	FOI	2004-2024	
76	Shetland Islands	FOI	2000-2024	
77	Shropshire	FOI	2001-2024	
78	Somerset	FOI	2001-2024	
79	South Yorkshire	FOI	2002-2024	
80	Southwark	FOI	2000-2024	
81	Staffordshire	FOI	2001-2024	
82	Strathclyde	FOI	2001-2024	
83	Suffolk	FOI	2005-2024	
84	Sutton	FOI	2005-2024	
85	Surrey	FOI	2005-2013	
86	Swansea	FOI	2002-2023	
87	Tayside	FOI	2002-2024	
88	Teesside	FOI	2004-2023	

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#	LGPS	Source	Coverage	Note
89	Tower Hamlets	Local Archives	2003-2024	FOI request refused
90	Tyne and Wear	FOI	1980-2023	
91	Waltham Forest	FOI	2004-2024	
92	Wandsworth	FOI	2005-2024	
93	Warwickshire	FOI	2002-2024	
94	West Midlands	FOI	2002-2016	
95	West Sussex	FOI	2001-2024	
96	West Yorkshire	FOI	2001-2024	
97	Wiltshire	FOI	2000-2016	
98	Worcestershire	FOI	2003-2010	