Long-term Investors, Demand Shifts, and Yields*

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Abstract

I use detailed data on bond and derivative positions of pension funds and insurance companies (P&Is) in the Netherlands to study demand shifts and their causal effect on yields. In particular, I exploit a reform in the regulatory discount curve that makes liabilities more sensitive to changes in the 20-year interest rate but less so to longer maturity rates. Following the reform, P&Is reduced their longest maturity holdings but increased those with maturities close to 20 years. The aggregate demand shift caused a steepening of the long-end of the yield curve with a decrease in the 20-year yield of 10 basis points and an increase in the 30-year yield of 20 basis points. Similar effects on yields appear in a large panel of European countries after EU insurance regulation implemented the same reform. My findings have important policy implications, as they indicate that the regulatory framework of long-term investors directly affects the governments' cost of borrowing.

Keywords: long-term investors, demand shifts, regulatory constraints, yield curve.
JEL classifications: G12, G18, G22, G23, G28.

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I. Introduction

Recent literature shows that long-term investors, such as pension funds and insurance companies, affect yields (e.g., Greenwood and Vayanos 2010; Domanski et al. 2017; Greenwood and Vissing-Jorgensen 2018; Klinger and Sundaresan 2019). The findings in this literature are consistent with the preferred habitat view: demand for specific maturities creates price pressure on bond markets. Demand shocks by these investors can affect yields in case of inelastic demand (e.g., Koijen and Yogo 2019) that for instance arises in the presence of limits to arbitrage (e.g., Vayanos and Vila 2021).

Because of data limitations, the literature so far primarily uses only price data to study the implications of the preferred habitat view on yields. As a result, there are two important questions largely left unanswered. First, what are the *quantities* behind observed yield effects? Second, what *drives* the demand for long-term bonds in the first place? For instance, to what extent is this demand driven by economic versus regulatory incentives and what is the role of investors' constraints?

My first contribution is to identify the causal effect of demand on yields by exploiting a regulatory reform. The unexpected nature of the reform also allows for a precise estimation of price elasticities of demand for several investor types. These price elasticities give insight in the mechanism behind the observed yield effects because they show which investor demand responds to a larger or lesser degree to changes in yields. My second contribution is to provide micro evidence of the drivers of demand for long-term bonds. I show that regulation regarding the valuation of the liabilities of long-term investors plays a key role in the demand for bonds with specific maturities, especially when these investors are close to their solvency constraints.

To study demand shifts and their causal effect on yields, I use the Dutch pension and insurance market as a laboratory. The Dutch pension and insurance market is particularly useful when studying the demand for long-dated assets and its effects on yields for three main reasons. First, the occurrence of an exogenous regulatory shock facilitates the clean identification of demand shifts and their effect on yields, which I will explain in detail in the following paragraphs. The second reason is the availability of detailed data on bond and derivative positions at the institutional level on the one hand, and data about the investors' liabilities on the other hand. While data on bond holdings are widely available for various investor types, detailed data on derivative positions and liabilities are typically scarce.[1] Yet, pension funds and insurance companies (henceforth: P&Is) hedge a substantial amount of their interest rate risk with derivatives. In order to accurately estimate their demand for long-dated assets, data on both bond and derivative positions are necessary. To explain the drivers of demand for long-dated assets, data on the liability structure of P&Is is also key. Third, the Dutch P&I market is economically important because the pension sector alone already covers 58 percent of the total assets of pension funds in the euro area (OECD 2020).[2]

I exploit the regulatory reform that the Netherlands introduced in July 2012. This reform changed the regulatory discount curve at which P&Is had to value their liabilities. With the reform, the long-end of the curve became *more* dependent on the 20-year interest rate and *less* dependent on longer maturity rates. The new discount curve uses market interest rates for maturities up to 20 years, while the interest rates for maturities that exceed 20 years equal a weighted average between the 20-year rate and a fixed rate: the Ultimate Forward Rate (UFR). The UFR is substantially higher than market interest rates and as a result, the regulatory discount curve reduces the value of the liabilities. At the same time, liabilities became more sensitive to changes in the 20-year interest rate but less so to changes in longer maturity rates.

[1] Detailed data on bond holdings, derivative positions, and liabilities are available for the US insurance sector and available for research, see e.g. Sen (2019), but these data do not (publicly) exist for US pension funds. Moreover, US insurance companies primarily invest their assets in corporate bonds while European ones invest the majority of their assets in government bonds. The data on European P&Is may therefore be better suited to study demand effects on government bond yields.

[2] In 2019, the assets under management (AUM) of pension funds equaled approximately €1.75 trillion and represented 58 percent of the total assets of pension funds in the euro area (OECD 2020). The AUM of insurance companies equaled €0.51 trillion and represented 6 percent of the total assets of insurance companies in the euro area (ECB 2021).

Greenwood and Vissing-Jorgensen (2018) already pointed out an increase in long-term yields around the announcement date of the reform which suggests that P&Is substantially changed their demand for long-term assets. Why does a change in the regulatory discount curve affect this demand? I theoretically argue that this demand arises mainly for two reasons: economic and regulatory hedging incentives. The long-term nature of P&Is' liabilities creates a natural preference for long-term bonds from a liability hedging perspective (Sharpe and Tint 1990; Campbell and Viceira 2002). Regulatory hedging incentives are particularly important when the regulatory framework does not fully reflect the economic state in which investors operate. For instance, the regulatory discount curve is important in solvency assessments, as the regulator uses it to estimate the solvency position of P&Is. In turn, solvency positions determine the amount pension funds can pay out to their retirees or insurance companies to their shareholders in terms of dividends. As a result, incentives to hedge the regulatory discount curve may increase if the curve diverges from the economic discount curve.

The reason to implement the regulatory reform was in anticipation of the European Union (EU) introducing a similar discount curve as part of the new Solvency II regulatory framework for insurance companies in 2016. In particular, the discussions at the time evolved around the convergence of regulatory discount rates to a stable level. Even though P&Is may have anticipated the regulatory reform as a result, they did not know the implementation date and the determinants of the shape of the UFR such as its level and slope. As such, how the reform would affect different maturities is unclear ex-ante and in particular the ex-post reliance of the curve on the 20-year interest rate. The less anticipated nature of the reform becomes evident by comparing the effects of other demand shocks on yields that are typically anticipated, such as Quantitative Easing (QE) programs (e.g., Krishnamurthy and Vissing-Jorgensen 2011; Meaning and Zhu 2011; McLaren et al. 2014; Schlepper et al. 2021; van Binsbergen et al. 2021). Indeed, Figure 1 shows a sudden increase in the 30-20 year yield spread at the implementation of the UFR, while long-term yields were already declining before the ECB announced and implemented its Expanded Asset Purchase Programme (EAPP) in early 2015. That said, to the extent that P&Is anticipated a lower sensitivity of their liabilities to very long-term interest rates, the estimated changes in yields may understate the true effects and the price elasticities that I estimate provide an upper bound of the true elasticities.

Moving to the results, I report the following key findings. First, consistent with the testable predictions of a mean-variance optimization problem in an asset-liability context with regulatory constraints, I find that the P&Is that are more exposed to the regulatory reform, that is, the ones with long-term liabilities, decrease their long-term bond holdings to a larger extent than less exposed ones. The aggregate decrease in long-term bond holdings is economically large: The total decline equals €9.15 billion which is equivalent to a decrease in demand of 29 percent relative to the pre-reform long-term bond holdings. At the same time, P&Is increase their aggregate bond holdings with maturities close to 20 years by €12.37 billion or 25 percent relative to the pre-reform 20-year bond holdings. Both effects are stronger for P&Is that are closer to their solvency constraints, because they have a stronger incentive to hedge the regulatory rather than the economic discount curve. Furthermore, the direct capital relief from the reduction in the liability values causes the P&Is to increase their allocation to equities and high yield government bonds. Overall, the results show that the regulatory reform leads to a reduction in economic hedges of interest rate risk and to a rise in risky asset exposures at the same time.[3]

Additionally, I find that my results on demand shifts in bond portfolios extend to derivative portfolios. In particular, I find a decline in the implied duration of portfolios of interest rate derivatives at the time of the implementation of the regulatory reform. Further, I combine the data on bond holdings with detailed data on derivative positions that became available as part of the European Market Infrastructure Regulation (EMIR) in 2016 to show a structural change in demand for long-dated assets with large exposures to the 20-year

[3] I perform several robustness checks to show that these findings cannot be explained by the ECB's asset purchasing programmes (APP).

interest rate but small exposures to longer maturity rates, especially for constrained P&Is.

Second, I estimate the effect of the aggregate demand shift in long-term bond holdings on yields. To cleanly identify the effect of demand on yields, I apply an instrumental variable approach that exploits the induced heterogeneous effect of the regulatory reform across maturity buckets. Based on the instrument, I find that the change in the regulatory discount curve results in an increase of the 30-year yield of approximately 20 basis points and to a decrease in the 20-year yield of 10 basis points. In addition, the instrument can be used to estimate demand curves as in Koijen and Yogo (2019) for the other institutions that hold Dutch debt, because the regulatory reform created an exogenous demand shift by the Dutch P&I sector that only affected the demand of other investor types through its effect on prices. The demand system gives further insight into the importance of various investor types in creating the observed yield effects. Consistent with the banks being most price elastic, banks substantially increased their 30-year bond holdings while at the same time reduced their holdings towards 20-year ones after the regulatory reform. To a lesser extent, the same pattern is also visible for the foreign sector. This finding provides evidence that banks and foreign investors buy (sell) long-term (20-year) assets from (to) the P&I sector.

Third, to generalize my findings, I provide evidence at the European level for the effects of the regulatory reform on yields. The UFR is an important aspect of the EU Solvency II regulation that was announced in August 2015 and took effect on January 1, 2016. Because insurance companies in the Netherlands are subject to similar regulations as other insurers in Europe, similar yield effects should exist for other European countries, at least to the extent the country has a sizeable insurance sector. I therefore test the effects of the UFR on a broad panel of 20 European countries and represent the demand for long-term bonds by the size of the insurance sector relative to the total debt outstanding of a country. My estimates show that for a one standard deviation increase in the size of the insurance sector, there was an increase in the 30-20 year yield spread of 4.7 basis points and a decrease in the 20-10 year spread by 7.5 basis points. Countries with a small insurance sector such as

Hungary and Portugal experienced negligible changes in yields; while Ireland and Denmark with large insurance sectors experienced a drop of 13-32 basis points in the 20-10 year spread and an increase of 8-20 basis points in the 30-20 year spread.

My findings have important policy implications. First, they show that the regulatory framework of investors has direct consequences for governments' costs of borrowing. Second, they show that regulation plays an important role in understanding the recent patterns in yields. For instance, long-term yields in Europe fell strongly in the second half of 2014. Long-term investors' demand for long-term bonds increases when interest rates decline that reinforces the decline in long-term yields (Domanski et al. 2017). My results show that this reinforcing effect weakens if the valuations of liabilities become less dependent on market interest rates. This finding indicates that policy-makers should take the regulatory framework of investors into account when analyzing the impact of monetary policies on yields.

Related Literature

This study contributes to the preferred habitat theory proposed by Culbertson (1957) and Modigliani and Sutch (1966), and later formalized in Vayanos and Vila (2021). They argue that some investors prefer specific maturities and that their demand for bonds with those maturities influences the interest rate for a given maturity. Greenwood and Vayanos (2014) study supply effects on yields. They find that supply shocks affect yields, because they change the duration risk that arbitrageurs carry. Similarly, Guibaud et al. (2013) model an investor-based yield curve. They show that an increase in the relative importance of a group of investors with a longer investment horizon, such as the young, has two related effects: it renders long-term bonds more expensive, and it increases their optimal supply by the government. I contribute to this literature by providing direct empirical evidence in favor of the preferred habitat theory by using a real world and exogenous demand shock as well as showing the origin of such a demand shock.

My findings also contribute to the work that empirically tests the implications of the preferred habitat theory or the demand-based view. For instance, Domanski et al. (2017) argue that the "hunt-for-duration" of insurance companies might have amplified the decline in bond yields in the euro area.[4] Similarly, Klinger and Sundaresan (2019) explain that negative 30-year US swap spreads are the result of underfunded pension plans optimally using swaps for duration hedging rather than long-term bonds. Additionally, Greenwood and Vayanos (2010) and Greenwood and Vissing-Jorgensen (2018) show that changes in regulation which increase the incentive to buy (sell) long-term bonds result in a decline (increase) in long-term yields around policy announcement days.[5] I contribute to this literature by studying the level and heterogeneity in the underlying quantities that cause the price effects documented in these papers. Understanding quantities together with prices is important to predict the effects of future regulatory or monetary policy changes on yields.

My study also contributes to the recent demand-based asset pricing literature. For instance, Koijen and Yogo (2019) propose an asset pricing model with flexible heterogeneity in the asset demand across investors. Koijen et al. (2017) and Koijen et al. (2020) apply this model to study the effects of quantitative easing on yields in the euro area. Pavlova and Sikorskaya (2021) provide a micro-foundation of inelastic demand for stocks that is driven by benchmarking incentives. I contribute to this work by providing an in-depth micro-foundation of asset demand for one particular sector, namely the P&I sector, and show that a fraction of this demand is inelastic because of regulatory incentives.[6]

My study also links to the literature that finds a high sensitivity of long-term nominal rates to high-frequency changes in short rates (Shiller et al. 1983; Cochrane and Piazzesi

[4] Ozdagli and Wang (2019) confirm that the tilt towards higher yield bonds in the portfolios of US life insurance companies when interest rates decline is driven by an increase in duration rather than credit risk.

[5] There is also a large body of literature that provides evidence of the demand-based view for stocks, e.g., Shleifer (1986); Wurgler and Zhuravskaya (2002); Greenwood (2005); Chang et al. (2015); Pavlova and Sikorskaya (2021).

[6] Additionally, my findings link to the recent intermediary asset pricing literature which directly models intermediaries and how they matter for asset prices, e.g., He and Krishnamurthy (2013). Like in Greenwood et al. (2018), Timmer (2018), Koijen and Yogo (2019), my results highlight the importance of incorporating heterogeneity across investor types in order to understand the effects of intermediaries on asset prices.

2002; Gürkaynak et al. 2005; Hanson 2014; Giglio and Kelly 2018; Hanson et al. 2021). In particular, Hanson (2014) and Hanson et al. (2021) find evidence that mortgage refinancing helps explain why long yields have temporarily overreacted to short rates since 2000 in the US. This amplification channel is less prevalent in the euro area because of the substantial fees that are involved in early repayment. In this study, I instead provide evidence for an alternative amplification channel, namely, the sensitivity of the regulatory discount rate to market interest rates. A decline in the short rate worsens the solvency positions of P&Is and therefore leads to a stronger incentive to hedge the regulatory discount curve that in turn, increases the demand for long-term bonds.

Finally, my findings link to the literature on the effects of regulation on the investment behavior of long-term investors. Ellul et al. (2011) show that fire sales occur in corporate bond markets because of the regulatory constraints imposed on insurance companies. Becker and Ivashina (2015) study the "reaching for yield" behavior of US insurance companies and show that conditional on credit ratings, insurance companies are biased towards higher yielding bonds. Sen (2019) finds distorted hedging incentives due to different regulatory treatments of interest rate risk for products with similar economic exposures. Becker et al. (2021) show that after a regulatory reform that eliminated capital requirements for MBS, US insurance companies have a reduced propensity to sell poorly-rated MBS investments. Ellul et al. (2020) show that variable annuities create incentives for insurers to hold more high risk and illiquid bonds. Consistent with these papers, my findings also align with the interpretation that regulation regarding capital requirements shapes the investment and hedging decisions of P&Is. Moreover, I mainly contribute to this literature by linking changes in hedging incentives to changes in long-term government bond yields.

The remainder of this study is organized as follows: I start by describing the introduction of the regulatory discount curve based on the UFR in Section II. Section III presents a simple model to derive testable implications on changes in long-term bond holdings. A description of the data is given in Section IV. In Section V, I test the empirical predictions that follow from the model by using a difference-in-difference specification; and in Section VI, I connect changes in holdings directly to changes in yields. Evidence for the effects of the regulatory reform on yields at the European level is provided in Section VII. Section VIII concludes.

II. Institutional setting - Ultimate Forward Rate (UFR)

The regulatory discount curve is important in solvency assessments, because regulators use it to estimate the liability value and hence the solvency position of P&Is. Fundamentally, the asset value compared to the liability value indicates whether P&Is can meet their nominal obligations. P&Is make important decisions based on solvency positions, such as the amount of dividends paid to the shareholders or the ability to index and cut pension rights. Since 2007, the valuation of assets in the Netherlands has been marked-to-market[7], and the Dutch Central Bank (DNB) constructs and publishes the regulatory discount curve to value the liabilities.

A. Regulatory discount curve with UFR

Prior to the start of July 2012, the DNB based the regulatory discount curve on the euro swap curve for all maturities and used market interest rates up to a maturity of 50 years. Afterwards, it extrapolated the interest rates for maturities beyond 50 years from the last observed forward rate. Because it based the regulatory discount curve on market interest rates only, the curve equaled the economic discount curve.

The DNB announced a change in the regulatory discount curve on July 2, 2012, in anticipation of the EU introducing its new Solvency II regulatory framework for insurance companies in 2016. The new curve would be similar to the regulatory discount curve in Solvency II that would become applicable to all European insurers. DNB announced a similar regulatory discount curve for pension funds on September 24, 2012.

[7] A marked-to-market valuation of the assets is in stark contrast with the life insurance industry in the US, where historical cost accounting is still commonly used across states (Ellul et al. 2015).

DNB's new regulatory discount curve uses an extrapolation method based on the UFR that is the convergence of long interest rates to a stable level. In essence, this new curve uses market interest rates up to a maturity of 20 years, and the DNB determines interest rates with maturities longer than 20 years by using a weighted average between the market interest rates and a fixed rate, the UFR. The main argument to justify the implementation of the UFR was that the market for long durations was fairly illiquid and only a few securities with such long durations existed. As a result, the DNB regarded the implied market interest rates as unreliable: a discount curve purely based on market data was highly sensitive to liquidity shocks and therefore also the solvency positions of P&Is. A regulatory discount curve based on the UFR solved this issue by making the long-end of the curve less dependent on market interest rates.[8]

Formally, the DNB constructed the regulatory discount curve as follows:

1. The euro swap rates for maturities of 1 to 10, 12, 15, and 20 years are converted to zero-coupon interest rates by means of bootstrapping.[9]

   For non-observable swap rates, the DNB estimates zero interest rates by assuming constant forward rates.

2. For insurance companies, forward rates exceeding maturities of 20 years are a weighted average between the 20-year forward rate and the UFR. The weight increases linearly in maturity, and the level of the UFR equals 4.2 percent. At a maturity of 60 years, forward rates equal the UFR:

$$f_{t,h-1}^{h,*} \begin{cases} f_{t,h-1}^{h} & \text{if} \quad 1 \leq h \leq 20, \\ (1 - w^{UFR}(h)) \times f_{t,19}^{20} + w^{UFR}(h) \times \text{UFR} & \text{if} \quad 20 < h < 60, \\ \text{UFR} & \text{if} \quad h \geq 60. \end{cases} \tag{1}$$

[8]Further details about the UFR are in Appendix B.

[9]Bloomberg also offers swap rates for all maturities from 1 to 20 years. However, the DNB refrained from using some of these interest rates because of less liquid markets.

For pension funds, the regulatory discount curve is slightly different and uses the corresponding market forward rate $f_{t,h-1}^{h}$ instead of the 20-year forward rate for maturities of 25, 30, 40, and 50 years.[10]

3. The DNB computes the zero-coupon interest rates $y_t^{(h)}$ as follows:

$$(1 + y_t^{(h)})^h = \prod_{n=1}^{h} (1 + f_{t,n-1}^{n,*}) \qquad \text{for} \qquad h = 1, 2, ...120. \tag{2}$$

The regulatory discount curve with the UFR has three important effects. First, the UFR decreases current liability values as liabilities are discounted against higher rates. Second, the UFR makes the regulatory discount curve less sensitive to parallel shifts in interest rate changes. Figure 2 displays these two effects. The red solid line shows the economic discount curve, and the blue solid line shows the economic discount curve after a parallel shock in interest rates of -1 percent. The dashed green line and the dotted black line show the same discount curves with the UFR. Third, the UFR results in a higher exposure to changes in the 20-year interest rate. Figure 3 displays this effect. A localized negative shock in the 20-year market interest rate as reflected by the blue dashed line reduces all the regulatory discount rates for maturities beyond 20 years that makes the liabilities particularly sensitive to changes in the 20-year interest rate under the new regulatory framework.[11]

[**Place Figure 2-3 about here**]

B. Impact of the UFR on the liability value

In order to show the effects of the UFR on the liability value, I compute it by using both the economic and the regulatory discount curve. For the average P&I, the peak of the cash

[10] The implication of the difference in the regulatory discount curve for insurers and pension funds is discussed in Section V.

[11] Note that a shock that affects the 20-year interest rate in isolation is not very common and is only used for illustrative purposes.

flow distribution of their liabilities is at a maturity of 20 years that reflects the importance of the UFR as half of the cash flows materialize at maturities beyond 20 years. Figure 4 shows these cash flows graphically. The cash flows allow me to compute the value of the liabilities both under the economic and regulatory discount curves. Formally, I compute $L_t = \sum_{h=0}^{120} CF(h) \exp(-h y_t^{(h)})$, where $CF(h)$ are the average projected pension payments for maturity h in which $y_t^{(h)} = y_{E,t}^{(h)}$ under the economic discount curve and $y_t^{(h)} = y_{R,t}^{(h)}$ under the regulatory discount curve.

In Table 1, I compute the liability values for the projected pension payments by using the discount curve with and without the UFR on September 30, 2012. Panel A shows that the liability value that uses the regulatory discount curve with the UFR declines by €664 million for the average pension fund, or a decrease of 4.23 percent. This decrease reflects the first effect of the UFR: a direct reduction in the regulatory liability values. The liability value after a -1 percent parallel shift in interest rates increases with €3,518 million when using the economic discount curve; while when using the regulatory discount curve, the increase equals €2,737 million, or a relative decline in interest rate sensitivity of 22.2 percent. This decline reflects the second effect of the UFR: a dampening effect of parallel changes in interest rates on liability values. Furthermore, this effect is particularly visible when looking at cash flows that materialize after 20 years in isolation. A parallel shock in interest rates of -1 percent increases the liability value by 31.7 percent less after the regulatory reform.

Panel B shows the third effect of the UFR: an increased sensitivity towards the 20-year market interest rate. A decrease in the 20-year interest rate increases the economic liability value by only 45 million, but the regulatory liability value increases by 1,222, or a relative increase of 2,615.6 percent. Again, this effect becomes even more apparent when looking in isolation at cash flows that materialize after 20 years.

[Place Table 1 about here]

[Place Figure 4 about here]

III. Model

I derive my main testable predictions from a partial equilibrium mean-variance optimization framework with assets and liabilities in which P&Is care about both their economic and regulatory solvency constraints. Economic and regulatory hedging demands were identical prior to the regulatory reform, while the hedging demands started to diverge afterwards. The extent to which economic and regulatory hedging demands deviate depends on the liability structure and solvency positions of P&Is. These factors result in heterogeneity in the effect of the regulatory reform on optimal long-term bond holdings across P&Is.

A. The financial market

The financial market consists of a risky asset and a set of bonds. The risky asset is denoted by S_t and its corresponding return by r^S_{t+1}. The set of bonds is denoted by B_t, and each bond is characterized by its maturity h and corresponding yield $y^{(h)}_t$. The return on each bond is defined as:

$$r^{(h-1)}_{t+1} = \ln(\frac{P^{(h-1)}_{t+1}}{P^{(h)}_t}) = y^{(h)}_t - (h-1)[y^{(h-1)}_{t+1} - y^{(h)}_t]. \tag{3}$$

The vector of maturities is denoted by $\mathbf{h}$, the vector of bond yields is denoted by $\mathbf{y}_t$, bond returns by $\mathbf{r}^B_{t+1}$, the return expectations by $\mathbb{E}_{i,t}[\mathbf{r}^B_{t+1}]$, and the covariance matrix by $\text{Var}_{i,t}[\mathbf{r}^B_{t+1}]$. I assume that the bond returns are imperfectly correlated, while the risky asset and the set of bonds are uncorrelated. Furthermore, I assume throughout that the yield curve can be determined using this set of bonds.

B. Long-term investors

The wealth of the long-term investor evolves as follows:

$$A_{i,t+1} = \Big(1 + r_f + w^S_{i,t}(r^S_{t+1} - r_f) + \mathbf{w}^{B\prime}_{i,t}(\mathbf{r}^B_{t+1} - r_f\mathbf{1})\Big)A_{i,t}, \tag{4}$$

where r_f equals the risk-free interest rate, $w^S_{i,t}$ equals the portfolio weight to risky assets, and $\mathbf{w}^B_{i,t}$ equals the vector of portfolio weights to bonds for investor $i = 1, ..., N$.

For the liabilities, I assume that P&Is have to pay out a fixed set of time-invariant cash flows each period that is characterized by the vector $\mathbf{CF}_i$ and its elements $\mathrm{CF}_i(h)$, that is, the cash flows for maturity h. A high cash flow $\mathrm{CF}_i(h)$ relative to the sum of the total cash flows $\sum_{h=1} \mathrm{CF}_i(h)$ means that a large fraction of the liabilities are due at maturity h.[12] Hence, the economic value of the liabilities at time t equals:

$$L^E_{i,t} = \sum_{h=0} \mathrm{CF}_i(h) \exp(-hy^{(h)}_t). \tag{5}$$

A first-order Taylor expansion in $hy^{(h)}_t$ results in the following economic value of the liabilities at time $t+1$ (proof Appendix C):

$$L^E_{i,t+1} \approx \mathbf{a}'_{i,t}(\mathbf{1} + \mathbf{r}^B_{t+1})L^E_{i,t}, \tag{6}$$

where

$$a_{i,t}(h) = \frac{\mathrm{CF}_i(h) \exp(-hy^{(h)}_t)}{L^E_{i,t}}. \tag{7}$$

The regulatory discount curve diverges from its economic counterpart in that its sensitivity to the market interest rate changes is different. The sensitivity of the regulatory discount curve to market interest rates is defined by $\boldsymbol{\xi}_L$, where $\boldsymbol{\xi}_L$ has the same length as the set of bonds. This sensitivity means that the economic and regulatory value of the liabilities are identical if $\xi_L(h) = 1$ for all h, which was the case prior to the regulatory reform. On the other hand, the regulatory value of the liabilities is insensitive to changes in the interest rate if $\xi_L(h) = 0$ for all h. An example of this insensitivity is a regulatory discount curve that is based on a fixed rate for all maturities.

[12] This assumption is realistic, because the pension funds are defined benefit in nature and insurance companies were not allowed to use variable annuities until 2016.

The regulatory reform that is the focus of this study indicates $\xi_L(h) = 1$ for $h < 20$, $\xi_L(h) > 1$ for $h = 20$, and $\xi_L(h) < 1$ for $h > 20$. Specifically, for the 20-year maturity, the sensitivity increases with the total sum of one minus the weights assigned to the UFR: $\xi_L(20) = \sum_{h=21}^{60} 1 - w^{UFR}(h)$, with the weights assigned to the UFR as described in Section II. For maturities beyond 20 years, $\xi_L(h) = 1 - w^{UFR}(h)$. Moreover, the market interest rate in (6) is replaced with the 20-year interest rate for maturities beyond 20 years. Thus, the regulatory value of the liabilities equals (proof Appendix C):[13]

$$L^R_{i,t+1} \approx \Big(\mathbb{1}_{h<20}\mathbf{a}'_{i,t}(\mathbf{1} + \mathbf{r}^B_{t+1}) + \mathbb{1}_{h\geq 20}\mathbf{a}'_{i,t}(\mathbf{1} + \boldsymbol{\xi}_L r^{20}_{t+1})\Big) L^R_{i,t}. \tag{8}$$

Further, I assume P&Is have mean-variance preferences over the assets minus liabilities or the surplus, which is similar to Sharpe and Tint (1990) and Hoevenaars et al. (2008). Following Koijen and Yogo (2015), I also assume P&Is care about the volatility in the regulatory funding ratio. P&Is have to make important decisions that are based on their funding positions, such as the amount of dividends to pay to shareholders or the ability to index pension rights. The optimization problem of P&Is then equals:

$$\arg\max_{\mathbf{w}_{i,t}} \mathbb{E}_{i,t}[\frac{A_{i,t+1}}{A_{i,t}}] - \frac{\gamma}{2}\mathrm{Var}_{i,t}[\frac{A_{i,t+1}}{A_{i,t}} - \frac{L^E_{i,t+1}}{A_{i,t}}] - \frac{\lambda(F^R_{i,t})}{2}\mathrm{Var}_{i,t}[\frac{A_{i,t+1}}{A_{i,t}} - \frac{L^R_{i,t+1}}{A_{i,t}}],$$

subject to

$$\mathbf{w}'_{i,t}\mathbf{1} = w^S_{i,t} + \mathbf{w}^{B\prime}_{i,t}\mathbf{1} \leq 1, \qquad w^S_{i,t}, w^B_{i,t}(h) \geq 0 \quad \forall h, \tag{9}$$

where γ equals the risk-aversion parameter, $F^R_{i,t} = \frac{A_{i,t}}{L^R_{i,t}}$, and $\lambda(F^R_{i,t})$ defines the importance of the regulatory funding ratio. As in Koijen and Yogo (2016) and Sen (2019), I assume that the variance of the regulatory funding ratio is proportional to $\lambda(F^R_{i,t})$ where $\lambda'(F^R_{i,t}) < 0$; or

[13] For pension funds, r^{20}_{t+1} is replaced by r^{25}_{t+1} for maturities between 25 and 30 years, by r^{30}_{t+1} for maturities between 30 and 40 years, and by r^{40}_{t+1} for maturities between 40 and 50 years. The model's implications remain similar, so for tractability of the model I leave out the difference between insurers and pension funds here but show the implications empirically in Section V.

in other words P&Is care more about the regulatory funding ratio when its low.[14]

As I show in Appendix C, solving for the optimal portfolio weights results in:

$$w_{i,t}^{S*} = \underbrace{\frac{\mathbb{E}_{i,t}[r_{t+1}^S - r_f] + \nu_{i,t} + \delta_{i,t}^S}{(\gamma + \lambda(F_{i,t}^R))\mathrm{Var}_{i,t}[r_{t+1}^S]}}_{\text{speculative portfolio}}, \tag{10}$$

$$\begin{aligned}\mathbf{w}_{i,t}^{B*} = & \underbrace{\frac{\mathbb{E}_{i,t}[\mathbf{r}_{t+1}^B - r_f\mathbf{1}] + \nu_{i,t}\mathbf{1} + \boldsymbol{\delta}_{i,t}^B}{(\gamma + \lambda(F_{i,t}^R))\mathrm{Var}_{i,t}[\mathbf{r}_{t+1}^B]}}_{\text{speculative portfolio}} + \underbrace{\frac{\gamma}{\gamma + \lambda(F_{i,t}^R)}\mathbf{a}_{i,t}\frac{1}{F_{i,t}^E}}_{\text{economic hedge portfolio}} \\ & + \underbrace{\frac{\lambda(F_{i,t}^R)}{\gamma + \lambda(F_{i,t}^R)}\mathbf{a}_{i,t}\frac{1}{F_{i,t}^R} \circ \left(\mathbb{1}_{h<20}\mathbf{1} + \mathbb{1}_{h\geq 20}\,\boldsymbol{\xi}_L \circ \frac{\mathrm{Cov}_{i,t}[r_{t+1}^{20}\mathbf{1}, \mathbf{r}_{t+1}^B]}{\mathrm{Var}_{i,t}[\mathbf{r}_{t+1}^B]}\right)}_{\text{regulatory hedge portfolio}},\end{aligned} \tag{11}$$

where $\nu_{i,t}$ equals the Lagrange multiplier for the restrictions of $\mathbf{w}_{i,t}'\mathbf{1} = 1$, $\boldsymbol{\delta}_{i,t}$ equals the Kuhn-Tucker multipliers for the restrictions that the portfolio weights are nonnegative, and ($\circ$) equals the Hadamard product.

The optimal demand for the risky asset consists of speculative demand only, because the liabilities are valued using the yield curve, and the bonds are assumed to be independent of the risky asset. The liability hedging portfolio consists of three components: the speculative demand, the economic hedging demand, and the regulatory hedging demand. The economic (regulatory) hedging demand equals the desired hedge against changes in the economic (regulatory) liability value. The heterogeneity in demand for long-term bonds across P&Is depends on two main factors. First, the demand for long-term bonds depends on the relative weights of the cash flow payments in the different maturity buckets $a_{i,t}(h)$. Second, the demand for long-term bonds depends on the weight assigned to the economic versus regulatory hedging demand which in turn, depends on the relative magnitudes of $\lambda(F_{i,t}^R)$ and γ that is driven by solvency positions $F_{i,t}^R$.

[14] To keep the model tractable, the functional form of $\lambda(F_{i,t}^R)$ is a reduced form of the strict constraint that the funding ratio should be higher than a certain threshold (e.g. Leibowitz and Henriksson 1989).

I now move on to characterize the change in demand. Throughout I indicate variables after implementation of the UFR with a plus sign ($^+$). Subtracting the optimal weights prior to the UFR (Equation (A.13) of the Appendix) from (11), the change in bond holdings due to the the regulatory reform becomes:

$$\mathbf{c}_{i,t} = \mathbf{w}_{i,t}^{B*+} - \mathbf{w}_{i,t}^{B*} = \underbrace{\frac{\mathbb{E}_{i,t}[\mathbf{r}_{t+1}^B - r_f \mathbf{1}] + \nu_{i,t}\mathbf{1} + \boldsymbol{\delta}_{i,t}^B}{\mathrm{Var}_{i,t}[\mathbf{r}_{t+1}^B]}\left(\frac{1}{\gamma + \lambda(F_{i,t}^R)} - \frac{1}{\gamma + \lambda(F_{i,t}^E)}\right)}_{\Delta \text{ in speculative demand}} + \underbrace{\frac{\lambda(F_{i,t}^R)}{\gamma + \lambda(F_{i,t}^R)}\left(\mathbf{a}_{i,t}\frac{1}{F_{i,t}^R} \circ \left(\mathbb{1}_{h<20}\mathbf{1} + \mathbb{1}_{h\geq 20}\,\boldsymbol{\xi}_L \circ \frac{\mathrm{Cov}_{i,t}[r_{t+1}^{20}\mathbf{1}, \mathbf{r}_{t+1}^B]}{\mathrm{Var}_{i,t}[\mathbf{r}_{t+1}^B]}\right) - \mathbf{a}_{i,t}\frac{1}{F_{i,t}^E}\right)}_{\Delta \text{ in liability hedge demand}} \tag{12}$$

Now, the speculative demand increases at all maturities, because $F_{i,t}^E < F_{i,t}^R$. For long maturities, $\lim_{h\to 60} \xi_L(h) \to 0$, and thus liability hedging demand declines with $\frac{\lambda(F_{i,t}^R)}{\gamma+\lambda(F_{i,t}^R)} a_{i,t}(h)\frac{1}{F_{i,t}^E}$. As shown in Section II, the regulatory reform decreases the liability values by 4 percent on average, and thus increases the regulatory funding ratio by approximately the same amount. However, the sensitivity to long-term interest rates declines by 22 percent (Table 1). As such, the decline in the liability hedging demand is much stronger than the increase in speculative demand. On the other hand, for maturities that are close to 20 years, $\lim_{h\to 20} \xi_L(h) \to \sum_{h=21}^{60} 1 - w^{UFR}(h) = 8.421$ (using the weights in Table A1), and therefore the liability hedging demand increases by $\frac{\lambda(F_{i,t}^R)}{\gamma+\lambda(F_{i,t}^R)} a_{i,t}(h)\left(\frac{1}{F_{i,t}^R}\xi_L(h) - \frac{1}{F_{i,t}^E}\right) > 0$.[15]

Finally, the model predicts a positive change in the risky asset holdings, because the regulatory reform led to direct capital relief ($\lambda(F_{i,t}^R) < \lambda(F_{i,t}^E)$):

$$c_{i,t}^S = w_{i,t}^{S*+} - w_{i,t}^{S*} = \frac{\mathbb{E}_{i,t}[r_{t+1}^S - r_f] + \nu_{i,t} + \delta_{i,t}^S}{\mathrm{Var}_{i,t}[r_{t+1}^S]}\left(\frac{1}{\gamma + \lambda(F_{i,t}^R)} - \frac{1}{\gamma + \lambda(F_{i,t}^E)}\right) > 0. \tag{13}$$

[15]The regulatory funding ratio for the average P&I goes from 0.99 to 1.03, and as such the inverse of the regulatory funding ratio decreases from 1.01 to 0.96. Thus, $\frac{1}{F_{i,t}^R}\xi_L(h) - \frac{1}{F_{i,t}^E} >> 0$.

C. Cross-sectional model predictions

The shift in demand in Equation (12)-(13) is heterogeneous across P&Is, and I describe the three important testable predictions about the cross-section next. The derivations are in Appendix D.

Prediction 1 - *P&Is with long liability durations reduce their very long-term maturity holdings and increase those with maturities close to 20 years more compared to P&Is with short liability durations.*

Prediction 2 - *P&Is with long liability durations increase their risky asset holdings more compared to P&Is with short liability durations.*

Prediction 3 - *P&Is close to their solvency constraint reduce their very long-term maturity holdings and increase those with maturities close to 20 years more compared to unconstrained P&Is.*

IV. Data

In this section, I describe the data sources that I use for my analysis (Subsection A) and provide summary statistics for the sample (Subsection B).

A. Constructing the dataset

I use data on Dutch security holdings (SHS) for four types of institutional investors: banks, insurance companies, investment funds, and pension funds over the period 2009q1-2018q4. The investment funds mainly consist of mutual funds. All institutions that report are domiciled in the Netherlands and the regulator decides which institutions have to report in order to have sufficient coverage in terms of AUM for every sector. Institutions have to report their holdings of all securities, both foreign and domestic, to the regulator on a quarterly basis.[16]

DNB gathers holdings data to compute, among other things, the Dutch balance of payments, international investment positions, and the financial accounts. Subsequently, it reports the holdings data to the ECB for the setup of the aforementioned statistics for the euro area. The data that I use are therefore also available for the euro area. I have two main reasons for using Dutch data for the main analysis. First, several European countries had already introduced the UFR in 2011 and 2012 but the holdings data that covers all countries and all securities became available only at the end of 2013. Moreover, the European data aggregates all institutions within a sector, while the Dutch data are at the institutional level. The institutional data allow me to make use of the cross-sectional variations. For instance, measuring the effects of the solvency positions on holdings is only possible when data are available at the institutional level. Despite these arguments, I augment the Dutch holdings data with the ECB holdings data in Section VI to quantify the effect of the UFR on yields and to estimate the demand curves of various investor types.[17]

The data provide bond and stock holdings with International Securities Identification Numbers (ISIN). Institutions report their positions at the start of the corresponding quarter, the total purchases and sales of each position, and the positions at the end of the quarter, all in euros. For both stocks and bonds, purchases and sales are in market values. The start and end holdings of stocks are available as the number of shares and market values. The start and end holdings of bonds are available as both nominal and market values.

The SHS database is linked to the Centralised Securities Database (CSDB). The aim of this database is to hold accurate information on all individual securities relevant for the statistical purposes of the European System of Central Banks, ECB (2010). I obtain the following relevant market information from the CSDB database: debt type, maturity dates, coupon rates, coupon frequencies, coupon type (e.g., fixed, floating or zero-coupon), last

[16]All institutions report their foreign holdings on a monthly basis, but this is not the case for domestic holdings. However, since Dutch institutions hold significant fixed income domestic holdings, I use quarterly data to ensure consistency.

[17]The data on bond holdings that exceed one-year maturities are available as of 2009 for the euro area.

coupon payment date, yield-to-maturity, and prices. I measure credit risk for corporate bonds using the distance to default (DTD) publicly available from the Credit Research Initiative at the National University of Singapore. Credit risk for government bonds is measured using credit ratings from Fitch. The data on total amounts outstanding are from the Dutch State Treasury Agency.

Next, I link the holdings data to the supervision databases. The supervision databases are from mandatory annual and quarterly statements that P&Is report to the DNB. P&Is have to report, among other things, solvency positions, liability durations, and asset allocations as well as the value of the assets and liabilities.

A pension fund's solvency position is assessed by computing its funding ratio, or its assets divided by its liabilities. The minimum funding requirement is a flat rate equal to a funding ratio of 104.2 percent. In contrast, the required funding ratio is based on a pension fund's risk profile and is calculated such that the probability that the funding ratio falls below 100 percent on a one-year horizon equals 2.5 percent. For a median pension fund this ratio amounts to a required funding ratio of 116 percent. In case a pension fund is not compliant with funding requirements, it files a recovery plan to the supervisor. Moreover, pension funds are not allowed to index pension rights if the funding ratio is below the minimum funding requirement. If the funding ratio falls below 90 percent a reduction in accrued benefits may be required.

In addition to funding ratios, insurance companies compute solvency ratios to assess their solvency positions. Solvency ratios equal the available capital divided by the required capital. Prior to the introduction of Solvency II in 2016, the solvency ratios of insurance companies were not risk-based. Before 2016, the DNB required capital to equal 4 percent of the value of the liabilities. At the introduction of Solvency II, it required capital to be computed like pension funds, except that it calculated capital such that the probability of the funding ratio falling below 100 percent on a one-year horizon equaled 0.5 percent, rather than the 2.5 percent for pension funds. In case an insurance company is not compliant with the minimum or required solvency requirements, it also files a recovery plan to the supervisor. Dividend policies are typically based on internal target solvency ratios. For instance, Allianz only pays out dividends if the solvency ratio exceeds 160 percent.[18]

The solvency ratios can be converted into funding ratios and vice versa. Because the model makes predictions based on funding ratios, I convert insurers' solvency ratios to funding ratios. Formally, prior to Solvency II, the regulation solvency ratios equaled $SR = \frac{A-L}{0.04L}$ which meant that the funding ratio equaled $\frac{A}{L} = 0.04 * SR + 1$. The solvency ratios under Solvency II are more complex and hence I hand-collect data on the assets and the liabilities for each insurer to compute the funding ratios.

B. The sample

The total sample covers 20 banks, 42 pension funds, 12 life insurers, 27 non-life insurers, and 160 non-equity mutual funds. This group of institutional investors represents around 80-90 percent of the AUM for all institutional investors domiciled in the Netherlands.[19]

I only analyze investors' direct holdings, that is, investments that are not made via other investor types such as mutual funds and collective investment undertakings (CIUs). The data, unfortunately, do not allow for a linkage between the indirect holdings of investors to their direct holdings, except for the two largest pension funds and the two largest insurance companies. For these P&Is, I know their shares in mutual funds so I can use both their direct and indirect holdings. Table 2 shows that after correcting the holdings for these four P&Is, the fraction of assets that are incorporated in my analysis equals on average 85 percent of the total AUM (direct+indirect).

Table 2 also shows that life insurance companies are the largest in terms of average AUM, followed by pension funds and banks. The average allocation to government bonds is 49, 45, and 46 percent for life insurers, non-life insurers, and mutual funds respectively, 38 percent for pension funds, and 23 percent for banks. Banks have the largest share of

[18]See https://www.allianz.com/en/investor_relations/share/dividend.html.

[19]See for details on reporting requirements https://statistiek.dnb.nl/statistiek/index.aspx.

corporate bonds at 67 percent followed by insurers at 34 percent and pension funds at 21 percent. Life insurers and pension funds also have the longest duration of their fixed income portfolios. The average bond durations are 8.4 and 7.3 years for life insurers and pension funds respectively; while the duration equals 1.78 years for banks, 4.86 for mutual funds, and 4.64 for non-life insurers. Pension funds have the largest equity allocation at 34 percent, while insurers invest only 12 percent of their assets in equities on average.

Moving to the liability side of P&Is, life insurers and pension funds have the longest liability durations at 11.8 and 18 years respectively. The liability duration of non-life insurers is much shorter at 4.2 years. The average funding ratio of pension funds equals 109 percent and 111 percent for that of insurers.

[Place Table 2 about here]

V. Empirical methodology

I turn to the main tests of the empirical predictions from my theoretical framework next. As the regulatory reform only affects the P&I sector, I focus on P&Is in this section and come back to the other investor types in Section VI. For bond holdings, I use the *notional* amounts in all my analyses such that market prices are not driving the results. A change in notional amounts reflects active choices by investors, which is exactly the focus of this study.

A. Long-term bond holdings and the regulatory reform

Figure 5 shows the average fraction of long-term bonds in the bond portfolio for P&Is over time, where long-term bonds are defined as bonds with maturities of 30 years or longer. Two quarters after the DNB implemented the UFR, there was a sharp decline in long-term bond holdings for both life insurers and pension funds. Long-term bond holdings slightly increased again towards the end of 2014 but remained substantially lower than the pre-UFR levels.

[Place Figure 5 about here]

To align the predictions of the model with the data, I use a difference-in-difference specification which compares long-term bond holdings before and after the implementation of the UFR. I conjecture that P&Is with long liability durations decrease long-term bond holdings more compared to investors with short liability durations:

$$\begin{aligned} w_{it}^{B} &= \alpha + \beta_1 D_{2011q2,i}^{L} \times \text{UFR}_t + \beta_2 \text{FR}_{it-1}^{-1} + \beta_3 \text{FR}_{it-1}^{-1} \times \text{PF}_i + \beta_4 D_{it-1}^{L} \\ &+ \beta_5 \text{AUM}_{it-1} + \nu_i + \lambda_t + \epsilon_{it}, \end{aligned} \tag{14}$$

where w_{it}^{B} is the bond allocation of P&I i at time t, UFR_t equals one after the implementation of the UFR and zero otherwise; $D_{2011q2,i}^{L}$ is a time-invariant characteristic that equals the liability duration as of 2011q2; FR_{it-1}^{-1} is the lagged inverse of the funding ratio minus one[20]; PF_i is a dummy variable that equals one if the investor is a pension fund; D_{it-1}^{L} is the lagged liability duration; AUM_{it-1} is the lagged total AUM; ν_i is the fund fixed effects; and λ_t is the time fixed effects.

The focus in the main specification is on the aggregate bond allocation to specific maturity buckets in order to easily interpret the total magnitude of demand shifts. I show that my results are robust to regressions at the security level in Section B.

I use the liability duration as of 2011q2 in the interaction term to ensure that the liabilities are not in any way affected by the regulatory reform, while at the same time ensuring representation of the liabilities as of the regulatory reform. The regression specification also allows for differences in responses to a decline in funding positions across pension funds and insurers. Although size does not appear in the model, it is added as a control because empirical studies have shown that size is an important driver of investment decisions (e.g., Pollet and Wilson 2008).

[20] An inverse of the funding ratio equal to one means that P&Is are neither funded or underfunded. Subtracting one from the inverse of the funding ratio has the advantage that the coefficient is easy to interpret with values above zero indicating underfunding.

Table 3 summarizes the results. P&Is with long liability durations decrease long-term holdings to a larger extent than the ones with short liability durations. At the same time, P&Is increased their bond holdings with maturities varying between 15 and 25 years, while they did not change their holdings of bonds with maturities less than 15 years. These results support the first prediction of my theoretical framework in Section III.

The effects are also economically significant. The total decline in long-term bond holdings approximately equals $\sum_{i=1}^{N} \hat{\beta}_1 \times D^L_{2011q2,i} \times AUM^B_{2012q1,i} =$ €9.15 billion, where $AUM^B_{2012q1,i}$ is the total AUM in bonds (nominal terms) for P&I i in the quarter before the regulatory reform was implemented in 2012q2. The decline is equivalent to a decrease of 29 percent relative to the pre-reform long-term bond holdings. Similarly, P&Is increased their 20-year bond holdings by €12.37 billion or 25 percent relative to the pre-reform 20-year bond holdings.[21] To give additional support for the economic effects, I have reestimated the regression based on Dutch government bond holdings alone. The aggregate decline in 30-year Dutch government bond holdings equals €2.53 billion. The corresponding amount outstanding equaled €12.13 billion at the implementation of the UFR, and hence, the total decline corresponded to 21 percent of its amount outstanding. Similarly, the aggregate increase in bond holdings with maturities between 15 and 25 years equaled €6.86 billion, or 23 percent of its amount outstanding.

[Place Table 3 about here]

My model also predicts that P&Is with long liability durations allocate more to risky assets after implementation of the UFR compared to those with short liability durations. To capture changes in risky asset allocations, I simultaneously study the asset allocation

[21] Because the regulatory discount curve is based on the euro swap curve, I have reestimated the regression specification using only investment grade European Union (EU) government bonds. The results do not change in sign and statistical significance, and if anything, increase in magnitude. Also, as another robustness check, I have added mutual funds to estimate (14): Mutual funds do not have liabilities and therefore their liability durations essentially equal zero. Adding mutual funds to the sample with a liability duration forced to zero does not affect the sign or the magnitude of the coefficients.

dynamics of stocks, corporate bonds, and government bonds. For corporate and government bonds, I also analyze the evolution of credit risk within both asset classes to distinguish between high risk or illiquid bonds (Ellul et al. 2020). Then, I use the following difference-in-difference specification to formally test the hypothesis:

$$
\begin{aligned}
w_{it}^{S} &= \alpha + \beta_1 D^{L}_{2011q2,i} \times \text{UFR}_t + \beta_2 \text{FR}^{-1}_{it-1} + \beta_3 \text{FR}^{-1}_{it-1} \times \text{PF}_i + \beta_4 D^{L}_{it-1} \\
&+ \beta_5 \text{AUM}_{it-1} + \nu_i + \lambda_t + \epsilon_{it}, \qquad (15)
\end{aligned}
$$

where w_{it}^{S} is the risky asset allocation of P&I i at time t.

Table 4 shows the results. The first column confirms that P&Is with long liability durations increase their equity allocation to a larger extent than the ones with short liability durations. A one standard deviation increase in the liability duration (6.49) expands the equity allocation by 1.37 percent but reduces the corporate bond allocation by 1.30 percent. The allocation to government bonds remains unaltered. Within corporate bonds, there is no evidence of a change in credit risk. On the other hand, a longer liability duration increases the fraction of government bonds allocated to countries with higher credit risk. Column 6 shows that a one standard deviation increase in the liability duration increases the fraction of high yield government bonds held by 1.63 percent. In sum, these findings show that P&Is move their assets away from corporate bonds to stocks and at the same time increase the riskiness of their government bond portfolios. These rebalancing activities may have important implications, because they reflect the potential spillover effects of demand shocks to other asset classes (Gabaix and Koijen 2021).

[Place Table 4 about here]

The final implication for the changes in holdings is that P&Is closer to their solvency constraint decrease (increase) long-term (20-year) bond holdings to a larger extent than unconstrained P&Is. I use a triple difference-in-difference estimation technique to test this hypothesis:

$$\begin{aligned} w^B_{it} &= \alpha + \beta_1 D^L_{2011q2,i} \times \text{FR}^{-1}_{2011q2,i} \times \text{UFR}_t + \beta_2 D^L_{2011q2,i} \times \text{UFR}_t \\ &+ \beta_3 \text{FR}^{-1}_{2011q2,i} \times \text{UFR}_t + \beta_4 \text{FR}^{-1}_{it-1} + \beta_5 \text{FR}^{-1}_{it-1} \times \text{PF}_i + \beta_6 D^L_{it-1} \\ &+ \beta_7 \text{AUM}_{it-1} + \nu_i + \lambda_t + \epsilon_{it}, \end{aligned} \tag{16}$$

where $FR^{-1}_{2011q2,i}$ is a time-invariant characteristic that equals the inverse of the funding ratio minus one in 2011q2.

Table 5 has a summary of the results. P&Is that are more constrained, that is, have a larger inverse of their funding ratio, decrease long-term bond holdings to a larger extent: A one standard deviation increase in the inverse of the funding ratio (0.08), increases the decline in long-term bond holdings by 1.4 percent for the P&Is with average liability duration and up to 2.8 percent for the ones with the longest liability durations, which equals a relative decline of 10-25 percent. Furthermore, P&Is that are more constrained also increase their holdings of bonds with maturities between 15 and 25 years to a larger extent than unconstrained ones which is consistent with the model's predictions.

[Place Table 5 about here]

B. Robustness main results

To ensure the validity of my findings, I perform two additional robustness checks. The first robustness check concerns the post period and the second one concerns an analysis at the security level.

1. Post period

The post period of my sample covers the ECB's Expanded Asset Purchase Programme (EAPP) which has also affected the investment behavior of P&Is. Indeed, as shown by

Domanski et al. (2017) and Koijen et al. (2020), P&Is increased their long-term bond holdings during QE that the widened duration gap between assets and liabilities when interest rates declined likely explains. However, the regulatory reform led to a decrease in long-term bond holdings as opposed to an increase which emphasized that QE could not explain my results, and if anything, the coefficient estimates underestimate the true effect of the regulatory reform on the decline in long-term bond holdings. To further corroborate that my findings are not driven by QE, I reestimate the regressions with a post period that ends in 2014q3 after which the ECB announced its EAPP on January 22, 2015. The results are in Appendix A2-A4 and both the signs and economic magnitudes remain largely unaltered.

2. Security level evidence

Furthermore, to ensure that my results are not driven by security characteristics other than a bond's maturity, I perform a similar regression as in Equation (14) at the security level. Formally, I run the following regression:

$$\begin{aligned} w_{sit} &= \beta_0 D^L_{2011q2,i} \times \mathbb{1}^{maturity\geq 30}_{st} \times \mathrm{UFR}_t + \beta_1 D^L_{2011q2,i} \times \mathbb{1}^{maturity\approx 20}_{st} \times \mathrm{UFR}_t \\ &+ \alpha_{is} + \gamma_{st} + \lambda_{it} + \epsilon_{sit}, \end{aligned} \tag{17}$$

where w_{sit} is the allocation to security s for P&I i at time t, $\mathbb{1}^{maturity\geq 30}_{st}$ is an indicator variable that equals one if the time to maturity of bond s is larger than or equal to 30 years at time t, and $\mathbb{1}^{maturity\approx 20}_{st}$ is an indicator variable that equals one if the time to maturity of bond s is between 15 and 25 years at time t. Fund-security fixed effects are denoted by α_{is} and capture time-invariant heterogeneity at the fund-security level, such as P&Is' differences in preferences for certain securities. Security-time fixed effects are denoted by γ_{st} and control for all time-variant and time-invariant security-specific characteristics that might correlate with maturity. Fund-time fixed effects are denoted by λ_{it} and control for time-variant and time-invariant P&I-specific characteristics.

Table A5 of the Appendix shows the results for all bonds in Columns 1-3 and safe (investment grade) EU government bonds in Columns 4-6. Because the regulatory discount curve is based on the euro swap curve, safe EU government bonds are the closest hedge assets and hence we should expect stronger results for this set of bonds. In all specifications, the coefficient β_0 is negative and statistically significant, while the coefficient β_1 is positive and statistically significant which is consistent with the previous findings. Quantitatively, Columns 3 and 6 show that the relative weight assigned to a 30-year (20-year) bond reduces (increases) by 14% (16%) for a P&I with average liability duration.

Table A6 of the Appendix shows the regression in Equation (16) at the security level:

$$\begin{aligned} w_{sit} &= \beta_0 D^L_{2011q2,i} \times \mathrm{FR}^{-1}_{2011q2,i} \times \mathbb{1}^{maturity \geq 30}_{st} \times \mathrm{UFR}_t \\ &+ \beta_1 D^L_{2011q2,i} \times \mathrm{FR}^{-1}_{2011q2,i} \times \mathbb{1}^{maturity \approx 20}_{st} \times \mathrm{UFR}_t + \alpha_{is} + \gamma_{st} + \lambda_{it} + \epsilon_{sit}. \end{aligned} \quad (18)$$

Consistent with constrained investors reacting more strongly to the regulatory reform, the coefficient for β_0 is negative and statistically significant, while the coefficient for β_1 is positive and statistically significant.

C. Interest rate derivatives and the regulatory reform

The empirical analysis thus far uses long-term bond holdings only. Moreover, investors can also use derivatives to manage interest rate risk, especially for very long maturities. Unfortunately, P&Is only started reporting their derivative holdings at the introduction of the EMIR regulation in 2016. However, as of the start of 2012, pension funds had already reported derivative positions on an aggregate level. I will therefore first show evidence of the change in the aggregate swap portfolios for pension funds at implementation of the UFR. Second, I will use the EMIR database to test the model implications that should still persist as long as the regulatory reform is in place.

1. Evidence from the supervisory reports

As of 2012, pension funds have reported the market value of interest rate derivative contracts aggregated by different contract types. Moreover, they have reported the values of these positions after a parallel shock in interest rates of +1 percent (-1 percent) and +0.5 percent (-0.5 percent). This reporting allows me to compute the dollar durations of the derivative positions.[22] Because the data on derivative positions are only available for two quarters prior to the regulatory reform, the time series is not long enough to statistically test if pension funds decreased their risk exposure to interest rates via derivatives as well. However, using the time series of the cross-sectional average implied duration of the derivative portfolios, I provide evidence that pension funds substantially decreased the duration of their derivative positions after the regulatory reform.

Formally, I approximate the dollar duration of the swap position as follows:

$$D_{p,t}^{\$} \approx -\frac{dV_t}{dr} = \frac{V_t^{-dr} - V_t^{+dr}}{2|dr|} \tag{19}$$

where V_t^{-dr} (V_t^{+dr}) is the value of the derivative portfolio after a negative (positive) change in interest rates; $D_p^{\$}$ is the dollar duration of the portfolio; and dr is the change in interest rates.

Figure 6 depicts the cross-sectional average implied duration of the swap portfolio over time, where the duration is computed as the dollar duration in (19) relative to the total AUM. The graph also shows the total balance sheet duration as the sum of the relative implied duration of the swap portfolio and the duration of the fixed income portfolio that then is multiplied by the allocation to fixed income. On average, pension funds have a balance sheet duration of 10 years. As the duration of the liabilities equals 18 years on average, this duration means that pension funds hedge approximately half of their interest rate risk. Importantly, the portfolio duration shows a decline at the implementation of the

[22] As the majority of the derivative positions consist of swaps, and swaps have a linear pay off function, I narrow down the analysis to the swap portfolio only.

UFR, which is consistent with the predictions of the model and the empirical findings for long-term bond holdings.

[Place Figure 6 about here]

2. Evidence from the EMIR data

To further strengthen the robustness of my findings, I empirically validate the cross-sectional predictions of the model after the regulation had already been in place for some time by using detailed data on derivative positions that were available as of 2016. The model described in Section III indicates that as long as the regulation is in place, P&Is are incentivized to have a substantially larger exposure to bonds with maturities close to 20 years, but less so to bonds with maturities exceeding 30 years. More importantly, the prediction that constrained P&Is hedge the regulatory discount curve more strongly as opposed to unconstrained P&Is should remain visible if the model is correctly specified. Testing both these predictions allows me to make more robust conclusions about the long-lasting effects of the UFR and to better understand the long-lasting price effects of the regulatory reform. I will start by introducing the data, and then I will provide the empirical results.

In response to the aftermath of the global financial crisis, regulators aimed to reduce risks and increase transparency in OTC derivative markets. The EMIR, which is similar to the Dodd-Frank Act, introduced reporting requirements to make derivative markets more transparent. The EMIR contains the derivative positions at the deal level of all counterparties for which at least one institution is established in Europe. Institutions report, among other things, the contract type (e.g., swaps, options, futures) and the details on the transaction such as notional, effective date, maturity date, information on price, payment frequencies, currencies, and the contract's counterparty. The Dutch regulator receives data on those derivative contracts for which at least one counterparty is established in the Netherlands. The database allows me to connect the derivative holdings of P&Is to their bond holdings by means of name matching.

For the purpose of this analysis, I focus on Euribor plain vanilla swaps for two main reasons. First, the regulatory discount curve is based on the euro swap curve; this basis means the best way to hedge liabilities is to buy into a receiver swap contract with underlying Euribor rates. Second, Euribor swaps represent over 70 percent of the total use of interest rate derivatives across P&Is which indeed indicates that P&Is primarily hedge their liabilities with swaps that use the Euribor as the underlying interest rate.

The EMIR database contains some quality issues with the data as acknowledged by, for instance, Perez-Duarte and Skrzypczynski (2019), so Appendix E lays out a detailed description of the cleaning of the data. Most importantly, I compute the market values of the swap contracts using the information available on each contract and compare these to the reported market values to correct for potential misreporting on the side of the swap contract (payer or receiver).

I then use the notional amount, side of the swap contract, and the maturity date of the contract to determine the net notional amount for different maturity buckets. Specifically, a receiver (payer) swap with a maturity of 30 years is equivalent to going long (short) on a bond with a 30-year maturity.[23] Then, I aggregate the bond and swap holdings over the maturity buckets to obtain the total exposure to each maturity bucket.[24] The results shown in the remainder of this section are based on 2019q4, but the results are qualitatively similar for other quarters.

Figure 7 displays the results that are separately aggregated for pension funds and insurance companies across institutions. The figure shows some interesting patterns. First, interest rate derivatives across maturity buckets make up more than half of the total exposure for maturities beyond 15 years, which is consistent with Figure 6. Second, the exposure peaks for maturity buckets $(15, 20]$ and $(20, 25]$, but substantially lowers for the maturities beyond 30 years. Third, the effect is stronger for insurance companies compared to pension

[23] Throughout I assume that the floating leg of the swap has zero interest rate risk.

[24] For bonds, the aggregate exposure is based on safe (investment grade) EU government bonds.

funds. The discrepancy arises from the slight difference in the way the regulatory discount curve is computed: for insurance companies, only the 20-year interest rates matters for long maturities; while for pension funds the 25-, 30-, 40-, and 50-year interest rates also play a role. In fact, the immediate observable difference in incentives between pension funds and insurers underscores the importance of the regulatory discount curve in shaping investment decisions.

[**Place Figure 7 about here**]

Figure 8 shows separate break downs of the P&Is into low versus high solvency positions, where high (low) is defined as those P&Is with a funding ratio above (below) the cross-sectional median funding ratio.[25] Interestingly, the P&Is with high solvency positions have much larger exposures to longer dated assets than the ones with low solvency positions. In particular, the aggregate amount invested in maturities beyond 30 years is €30 billion for P&Is that are unconstrained compared to approximately €5 billion for the ones that are constrained. This finding is consistent with the model and, more importantly, further corroborates the finding that constrained P&Is in particular hedge the regulatory rather than the economic discount curve.

[**Place Figure 8 about here**]

VI. The effect of demand shifts on long-term yields

In this section, I estimate the effect of the regulatory reform on yields by using the construction of the UFR as an exogenous shock to demand that affects yields differently at different maturities. I then use this construction as an instrument to estimate the effect of yields on Dutch government bond holdings for various investor types by using the framework of Koijen and Yogo (2019). Finally, I perform a calibration exercise to estimate the effect of

[25]The break down is separately computed for insurers and pension funds, so each group contains an equal number of pension funds and insurance companies.

the regulatory reform on the entire yield curve.

A. *The connection between portfolio holdings and yields*

The regulatory reform increased Dutch long-term bond yields as already pointed out by Greenwood and Vissing-Jorgensen (2018). Figure 1 (Panel a) displays the 30-20 government bond spread. The spread increased significantly after the announcement of the UFR and remained at a higher level thereafter. I will show that the increase in the 30-20 year bond spread is the result of both an upward pressure on the 30-year yield as well as downward pressure on the 20-year yield.

In order to reach this goal, I estimate the demand curves of the other investors that hold Dutch debt and thus have to absorb the demand shock that is caused by the Dutch P&I sector. Using the demand curves, I can measure their price elasticities of demand which in turn, allow me to study price effects as well as the importance of various investor types in creating price effects.

To estimate demand curves, I apply the asset demand system developed by Koijen and Yogo (2019). Formally, investor i's investment in Dutch government bonds within maturity bucket h is denoted by $B_{it}(h)$, and the investment in the outside asset is denoted by O_{it}. I cannot observe what investors consider to be the outside asset, so I use the 10-year German yield as a proxy for the outside asset, because German government bonds are good substitutes for Dutch ones.

The portfolio weight in the framework of Koijen and Yogo (2019) is then defined as:

$$w_{it}(h) = \frac{B_{it}(h)}{O_{it} + \sum_{h=1}^{H=7} B_{it}(h)} = \frac{\delta_{it}(h)}{1 + \sum_{h=1}^{H=7} \delta_{it}(h)}, \tag{20}$$

where $\delta_{it}(h) = w_{it}(h) w_{it}^{-1}(0) = B_{it}(h) O_{it}^{-1}$ and $w_{it}(0) = 1 - \sum_{h=1}^{H=7} w_{it}(h)$ equals the fraction invested in the outside asset. The demand of investor i for government bonds with maturity

h is a function of bond yields and characteristics (Koijen et al. 2020):

$$\begin{aligned} \ln B_{it}(h) &= \ln \delta_{it}(h) + \ln O_{it} \\ &= \hat{\alpha}_i + \beta_{0i} y_t(h) + \beta_{1i}' x_t(h) + \hat{\beta}_{2i} y_t^{DE} + \beta_{3i} \ln(B_{2009q1,i}(h)) + \epsilon_{it}(h), \end{aligned} \quad (21)$$

in which $\hat{\alpha}_i = \alpha_i + \ln O_i$, $\hat{\beta}_{2i} = \beta_{2i} + \psi_i$, $y_t(h)$ is the average yield for maturity bucket h, $x_t(h)$ represents bond characteristics, and y_t^{DE} is the 10-year German yield and captures alternative investment opportunities outside of the Netherlands.[26] Moreover, the inclusion of the initial holdings, $\ln(B_{2009q1,i}(h))$, captures time-invariant omitted characteristics.

Koijen and Yogo (2019) show that (21) is consistent with a model in which investors have mean-variance preferences over returns, assume that returns follow a factor model, and assume that both the expected returns and factor loadings are affine in a set of characteristics. The component of demand that is not captured by prices, characteristics, and time-invariant characteristics, $\epsilon_{it}(h)$, is referred to as latent demand.

Moving to the bond characteristics, I assume that yields are primarily driven by duration and convexity that is measured as the duration squared. Safe, (long-term) government bond returns are indeed primarily driven by duration and convexity. I also add the average coupons and the total amount outstanding (TAO) as characteristics that drive demand for bonds. Investors who aim to match their cash flows might have a preference for coupon bonds, and TAO is a measure of liquidity that potentially leads to higher or lower demand for certain maturity buckets.

In order to obtain consistent estimates of the parameters in (21) using OLS, one has to assume that characteristics are exogenous to latent demand. However, a positive latent demand for Dutch government bonds of a particular maturity may result in lower yields. The demand curves are therefore estimated using an instrumental variable approach. I use

[26] The assumption that holdings of the outside asset move only due to changes in the German yield result in $O_{it} = O_i \exp(\psi_i y_t^{DE})$ and hence the natural logarithm results in the terms $\ln O_i$ and $\psi_i y_t^{DE}$ that can be placed on the right-hand side of Equation (21).

the weights assigned to the UFR as an instrument for changes in demand. Even though investors may have anticipated the UFR, they did not know the determinants of the shape of the UFR such as its level and the slope.[27] As a result, the demand shift by the P&I sector is exogenous and can be used to estimate the demand curves of the other investors, because the demand shift only affects holdings of other investor types through its effect on prices.

The instrument is constructed in such a way that its negative for the maturity buckets $(15, 20]$ and $(20, 25]$ because of the excess demand for 20-year maturity bonds, whereas the instrument is positive for the maturity buckets $(25, 30]$ and $(30, \infty)$ because of the reduced demand for long-term maturities. Specifically, the instrument is constructed as the average weight assigned to the UFR for each maturity bucket summarized in Table A1 of the Appendix minus the total weight assigned to the 20-year interest rate for the maturities 20-40 years and is equally distributed over the $(15, 20]$ and $(20, 25]$ maturity buckets. The instrumental variable is then defined as $z_t(h) = \xi(h)\text{UFR}_t$, where $\xi(h)$ is the average weight assigned to the UFR for maturity bucket h.[28] The first-stage regression of the instrumental variable estimator equals:

$$y_t(h) = \gamma_{0i} + \gamma_{1i} z_t(h) + \gamma_{2i}' x_t(h) + \gamma_{3i} y_t^{DE} + \gamma_{4i} \ln(B_{i,2009q1}(h)) + \epsilon_t(h). \tag{22}$$

[Place Table 6 about here]

The first stage is summarized in Column (1) of Table 7 for the foreign sector.[29] The t-statistic equals 5.85 and is higher than the proposed threshold of 4.05 by Stock and Yogo (2005) for rejecting the null of weak instruments at the 5 percent level. Therefore, this value

[27] In fact, in discussions between the regulator and the P&I sector about the UFR before its implementation, the regulator prohibited P&Is to trade on this information. One specific insurer, Delta Llyod, did not comply and as a result, received a €22.7 million fine: `https://www.rechtspraak.nl/Organisatie-en-contact/Organisatie/Rechtbanken/Rechtbank-Rotterdam/Nieuws/Paginas/Publicatie-uitspraken-over-boete-en-heenzending-bestuurder-Delta-Lloyd.aspx`.

[28] Alternatively, I obtain similar results when I use the estimated changes in demand from Section V as the instrument.

[29] The first-stage coefficient estimates for the other sectors range from 0.30 (for the sector other) to 0.33 (for the sector banks).

indicates that the instrument is not weak. A coefficient of 0.30 means that government bond yields with maturities between 16 and 20 years decreased by 12 basis points and maturities between 21 and 25 years decreased by 5 basis points but maturities between 26 and 30-years went up by 17 basis points and maturities longer than 30-years went up by 27 basis points.

To estimate the demand curves, I extend the Dutch holdings data with the ECB holdings data to obtain a larger coverage of Dutch government bond holders. The following sectors in the euro area are incorporated into my analysis: banks, insurance companies, and pension funds except those in the Netherlands, mutual funds, and other sectors (households, non-bank financial institutions etc.). I aggregate the holdings of all sectors, because I do not have investor specific characteristics for these investor types to take advantage of cross-sectional heterogeneity within types. The investments of the foreign sector are defined as the difference between the total amount outstanding minus the holdings of the euro area investors.

Unfortunately, the data does not allow me to incorporate holdings of interest rate derivatives to estimate demand curves, because the instrument requires data before and after the regulatory reform. However, as shown in the previous section, the swaps are used in a similar way as bonds: the P&I sector uses interest rate swaps to primarily increase their exposure towards the 20-year interest rate instead of longer ones, which provides suggestive evidence of similar estimates for the demand curves in case one would be able to include interest rate derivative holdings.

Columns 2-6 of Table 7 show the estimates of the demand system. The demand curves for all investors are downward sloping, except they are slightly upward sloping for the P&I sector outside the Netherlands. Moreover, all investor types prefer bonds with large outstanding amounts (liquid bonds), and foreign investors and banks prefer bonds with strong convexity.

[Place Table 7 about here]

I can use the demand system to connect prices to the elasticity of demand by taking the derivative of quantities with respect to price for all investor types (Koijen and Yogo 2019;

Koijen et al. 2020):

$$\frac{\partial q_{it}(h)}{\partial p_{it}(h)} = 1 + 100\frac{\beta_{0i}}{T_t(h)}(1 - w_{it}(h)), \quad (23)$$

where lowercases are the logs of variables, and $T_t(h)$ is the average maturity for maturity bucket h. To compute $w_{it}(h)$, I use the investments in all bonds.

The demand elasticities with respect to price for each investor type are summarized in Table 8. A demand elasticity close to zero indicates that demand is inelastic, and a large value indicates that demand is sensitive to the price. Banks have the highest demand elasticity, followed by foreign investors. The market clearing condition means that the weighted average elasticity matters for deriving yield effects and equals 4.11. To the extent that P&Is anticipated a lower sensitivity of their liabilities to very long-term interest rates, the estimated changes in yields may understate the true effects and the price elasticities that I estimate provide an upper bound of the true elasticities.

As in Koijen et al. (2020), demand elasticities are substantially higher than the estimates for stock markets; for example, Chang et al. (2015) find an elasticity close to one. However, the weighted average price elasticity of demand is slightly higher than measured in Koijen et al. (2020) (a difference of 12 percent). This finding can be explained by the fact that the demand shock is caused by the P&I sector. Excluding the P&I sector to absorb demand shocks means that the shock is absorbed by a less inelastic investor base, because the demand curves of P&Is are more inelastic or even upward sloping compared to the other investor types. Moreover, I find that banks are more elastic than mutual funds, while Koijen et al. (2020), who estimate price elasticities at the issuer-country level, find the opposite. The likely explanation of the discrepancy is that mutual funds typically target a specific duration, namely the duration of benchmark indices. Therefore, bonds of different maturities may not be good substitutes, while government bonds issued by different (safe) countries may be good substitutes.

Interestingly, banks being most price elastic coincides with the finding that these investors substantially lowered their exposure to 20-year bonds after the regulatory reform, while at the same time they increased their holdings of 30-year bonds (Figure 9). Quantitatively, banks moved from holding 4 percent of the total amount outstanding of bonds with maturities close to 20 years to zero percent after the regulatory reform. Likewise, they moved from holding 1 percent of the total amount outstanding of bonds with maturities exceeding 30-years to 18 percent after the regulatory reform. To a lesser extent, this pattern is also visible for the foreign sector with a total decrease (increase) in 20-year (30-year) bond holdings of 5 (12) percent.[30] This finding provides evidence that banks and foreign investors bought long-term bonds from the P&I sector, while at the same time they sold bonds with maturities close to 20 years.[31]

In order to derive asset pricing effects from the demand system, I can perform a simple back-of-the-envelope calculation. Pension funds and insurers sell 21 percent of the amount outstanding of 30-year Dutch government bonds. This percentage means a price effect equal to $21\%/4.11 = 5.11\%$. For a bond with a maturity of 30-years, this percentage means an increase in long-term yields of 17 basis points, which is close to the price effect found for the first-stage regression. The heterogeneity in price elasticities across institutions indicates that price effects are smaller if a larger share of the debt outstanding is held by more elastic investors, such as banks, while they are larger if a higher share is held by less elastic investors, such as pension funds.

[Place Figure 9 about here]

[Place Table 8 about here]

[30] Notice that these findings cannot be explained by QE, because QE was announced in 2014, while the comparison of the investor weights is based on data from 2011-2013.

[31] It bears emphasizing that the change in the distribution of investor holdings over maturities buckets after the regulatory reform can only provide evidence on who bought (sold) long-term (20-year) bond holdings from the P&I sector. Transaction level data are required to give a definite answer and are unfortunately unavailable.

B. The effect of the regulatory reform on the yield curve

Thus far, I have shown localized effects of the regulatory reform on long-term bond yields. In this section, I aim to estimate the effect of the regulatory reform on the entire yield curve. In order to achieve this goal, I introduce a representative myopic investor, or an arbitrageur, and impose market clearing as in Vayanos and Vila (2021). This approach means that the change in holdings by the long-term investors derived in Section III has to be absorbed by a representative myopic investor. As for the long-term investors, I assume that the myopic investor has mean-variance preferences over excess returns. Moreover, the investors do not face borrowing or short-sale constraints. Therefore, the optimal portfolio equals:

$$\boldsymbol{\alpha}_t^{B*} = \frac{\mathbb{E}_t[\mathbf{r}_{t+1}^B - r_f\mathbf{1}]}{\gamma \mathrm{Var}_t[\mathbf{r}_{t+1}^B]} \tag{24}$$

Assuming that interest rate expectations did not change because of the implementation of the UFR, the change in yields equals (proof Appendix F):

$$\mathbf{y}_t^+ - \mathbf{y}_t \quad = \quad -\frac{1}{B_t}\frac{\gamma \mathrm{Var}_t[\mathbf{y}_{t+1}](\mathbf{h}-\mathbf{1})(\mathbf{h}-\mathbf{1})'}{\mathbf{h}}\sum_{i=1}^{N}\mathbf{c}_{i,t}A_{i,t}, \tag{25}$$

where B_t is the aggregate wealth of the arbitrageurs and the other variables are as defined in Section III.

I calibrate the effect on the yield curve by making the following assumptions. First, as is common in the asset pricing literature, I set $\gamma = 3$. I estimate the covariance matrix by using a VAR(1) model.[32] For the VAR(1) model, I use the daily 1, 3, 5, 10, 15, 20, and 30-year Dutch zero-coupon bond yields obtained from Bloomberg over the period 1998 to June 30, 2012, when the UFR was implemented.[33] The aggregate demand shock $\sum_{i=1}^{N}\mathbf{c}_{i,t}A_{i,t}$ and the wealth of the arbitrageurs B_t is taken relative to total Dutch debt. Therefore,

[32] I leave to future research a full calibration of the model where yields are derived endogenously as in Vayanos and Vila (2021).

[33] Further details on the VAR estimation are in Appendix F.

the demand shock $\sum_{i=1}^{N} \mathbf{c}_{i,t} A_{i,t}$ is equal to the total increase (decline) in 20 (30) year bond holdings as estimated in Section V relative to the total amount outstanding. These estimates consider $\sum_{i=1}^{N} A_{i,t}\mathbf{c}_{i,t}(20) = 23\%$ and $\sum_{i=1}^{N} A_{i,t}\mathbf{c}_{i,t}(30) = -21\%$, while $\sum_{i=1}^{N} A_{i,t}\mathbf{c}_{i,t}(h) = 0$ for $h = 1, 3, 5, 10, 15$. For the wealth of the arbitrageurs, suppose, as in Vayanos and Vila (2021), that the arbitrageurs are the hedge funds. Their wealth equaled 19.8 billion and total Dutch debt equaled 280 billion in 2012. These values mean that the arbitrageurs' wealth equals 7.07% of the total Dutch debt.[34]

Figure 10 shows the actual yield curve prior to the regulatory reform and the calibrated yield curve after the change. Yields at shorter maturities went up, because the negative shock to the 30-year yield outweighs the positive shock to the 20-year yield at shorter maturities due to a higher conditional covariance of short maturity bond returns with the 30-year bond return than with the 20-year one (i.e., longer maturity bonds are riskier). For maturities beyond 20 years, the yield curve moves from a hump-shaped pattern to an upward sloping pattern. Because the data do not allow for precisely pinning down the fraction of arbitrageurs, I also estimate the change in the yield curve using the upper bound for the fraction of arbitrageurs equal to 29.5% as used in Vayanos and Vila (2021). In that case, the yield effects are substantially smaller and the shape of the yield curve does not materially differ from the yield curve prior to the regulatory reform. However, the substantial yield effects found in the previous section indicate a fraction of arbitrageurs that is substantially below the upper bound of 29.5%.

[Place Figure 10 about here]

[34] For the total wealth of hedge funds in 2012 in the Netherlands, see, for instance, https://www.bnr.nl/nieuws/beurs/10167851/pensioenbeheerders-spekken-hedgefondsen and https://financieel-management.nl/artikelen/cijfers-dnb-vermogen-hedgefondsen-stijgt-opnieuw/.

VII. Effects of the UFR at the European level

The UFR is an important aspect of the EU Solvency II regulation that was announced in August 2015 and took effect as of January 1, 2016. Because insurance companies in the Netherlands are subject to similar regulations as other countries in Europe, there should be similar yield effects in other European countries.[35] In order to test for the effect of the UFR on a broader scale, I construct a panel that comprises 20 European countries subject to Solvency II regulations and regress the yield spreads of these countries on a proxy for insurance demand in those countries that is interacted with a dummy that equals one after the announcement of the UFR.[36]

The following countries are included in the panel: Austria, Belgium, Bulgaria, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Netherlands, Norway, Poland, Portugal, Slovakia, Spain, Sweden, and the UK over the period from 2006-2020. The size of the insurance sector differs substantially in these countries (Scharfstein 2018; Greenwood and Vissing-Jorgensen 2018). Therefore, I use the size of the insurance sector in each country relative to its debt as a proxy for insurance demand for long-term bonds. The larger the size of the insurance sector relative to debt, the higher demand for long-term assets in that country. I obtain the sizes of the insurance sectors from EIOPA Insurance Statistics.[37]

In the regressions, I control for other variables that determine yield spreads: the 10-2 year government bond spread, the debt-to-GDP ratio, the CDS spread, and the age of the population (measured by the fraction of the elderly relative to the total population). The 10-2 year government bond spread controls for the slope of the term structure (Scholtens and Tol 1999). The debt-to-GDP ratio controls for the fact that countries with more debt,

[35] The level and the convergence of the regulatory discount curve to the UFR is identical for euro area countries but deviates for countries outside the euro area. In particular, the level of the UFR depends on the inflation level for non-euro area countries. For more details, see e.g. EIOPA (2017), page 8/135.

[36] The UFR dummy equals one as of the announcement of the UFR in August 2015, except for the countries Denmark, the Netherlands, and Sweden, because those countries implemented the UFR earlier, and hence, the UFR dummy equals one as of June 2012, July 2012, and February 2013, respectively.

[37] See https://www.eiopa.europa.eu/tools-and-data/insurance-statistics_en

or a higher supply of bonds, likely have lower yields (e.g. Greenwood and Vayanos 2014). CDS spreads control for the effects of differences in default risk across countries on yield spreads. The age of the population controls for countries with older populations that have more government debt supply and larger term spreads (Guibaud et al. 2013). In some of the specifications, country fixed effects are also included to control for omitted persistent country characteristics that potentially affect yield spreads, such as differences in countries' financial systems.

I then run the following regression:

$$y_{c,t}(h) - y_{c,t}(s) = \alpha + \beta_0 \text{SIZEIC}_c^{2015} \times \text{UFR}_t + \beta_1 X_{c,t} + \lambda_t + \nu_c + \epsilon_{c,t}, \tag{26}$$

where $y_{c,t}(h) - y_{c,t}(s)$ is the h minus s year government bond spread in country c at time t; UFR_t equals one as of August 2015 and zero otherwise (except for Denmark, the Netherlands, and Sweden, where the dummy equals one as of June 2012, July 2012, and February 2013, respectively); SIZEIC_c^{2015} is the measure of the demand for long-term bonds by the insurance sector of country c in 2015; $X_{c,t}$ includes country controls: 10-2 year spread, debt-to-GDP, CDS spread, and age; λ_t are time fixed effects; and ν_c country fixed effects.

Table 9 has a summary of the results. Countries with larger demand for long-term bonds by the insurance sector have higher 30-20 year yield spreads but lower 20-10 year yield spreads, which is consistent with the findings for the Dutch P&I sector. A one standard deviation increase in insurance demand (0.715), increases the 30-20 year bond spread after the introduction of the UFR by 4.7 basis points and lowers the 20-10 year spread by 7.5 basis points. Countries with a small insurance sector such as Hungary and Portugal experienced negligible changes in yields, while Ireland and Denmark with large insurance sectors experienced a drop of 13-32 basis points in the 20-10 year spread and an increase of 8-20 basis points in the 30-20 year spread, respectively. Table A7 of the Appendix shows that similar effects occur when I use an alternative measure of insurance demand that multiples the size of the insurance sector with the aggregated liability duration of insurance companies. Multiplying the size of the insurance sector with the liability duration controls for differences in the liability structure of insurance companies across countries and thereby more accurately measures the demand for long-term assets.

Overall, these findings show that the effects of the UFR on yields are visible beyond the Netherlands, and more importantly, that these effects are created through a shift in demand for long-term assets by the P&I sector.

[Place Table 9 about here]

VIII. Conclusion

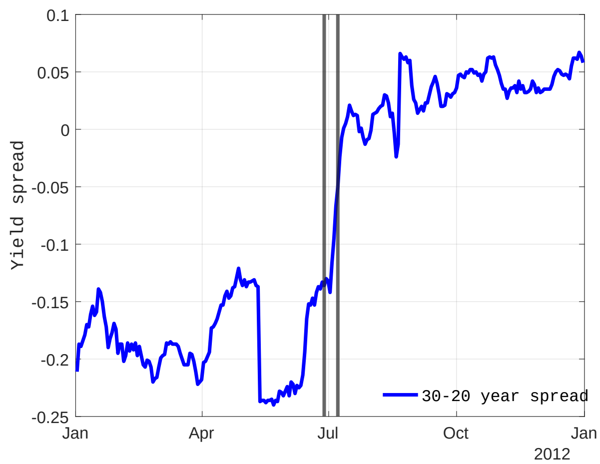
In this study, I use holdings data and price data simultaneously to study demand shifts and their causal effect on yields. In particular, I exploit a change in the regulatory discount curve at which the liabilities of long-term investors are evaluated and find a structural change in demand for long-dated assets that led to a downward pressure on 20-year yields but to an upward pressure on longer maturity yields.

Exploiting the heterogeneity in demand shifts across long-investors shows that constrained investors reacted more heavily to the regulatory reform compared to unconstrained ones which has important implications for the vulnerability of the pension and insurance sector going forward.

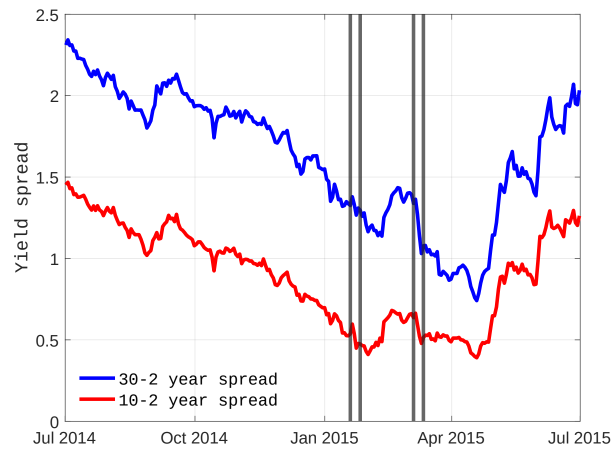
My results also show that regulation plays a nontrivial role in the demand for long-term bonds which in turn, affects the yields of these bonds. This finding has direct implications for the role of regulation in the government's cost of borrowing. Moreover, this finding shows the relevance of incorporating the regulatory framework of investors to analyze the effects of conventional and unconventional monetary policies on yields.

Figure 1. **Dutch government bond yield spreads: UFR versus QE**

This graph shows Dutch government bond yield spreads around the introduction of the UFR (Panel a) and the announcement of the Expanded Asset Purchase Programme (EAPP) of the ECB (Panel b). Panel a show the 30-20-year spread and the vertical lines are three days before and after the announcement (and implementation) of the UFR on July 2, 2012. Panel b shows the 30-2 year and 10-2 year spread and the vertical lines are three days before and after the announcement of the EAPP on January 22, 2015 and its implementation on March 9, 2015. Yield spreads are in percentage points.



(a) Yield spread UFR



(b) Yield spread QE

Figure 2. **Regulatory discount curve parallel shift interest rates**

This graph shows the economic discount curve (solid red line) and the regulatory discount curve (dashed green line) at implementation of the UFR on September 30, 2012. The graph also shows the economic (solid blue line) and regulatory (dotted black line) discount curve after a parallel shock in market interest rates of $\triangle y_t = -1\%$.

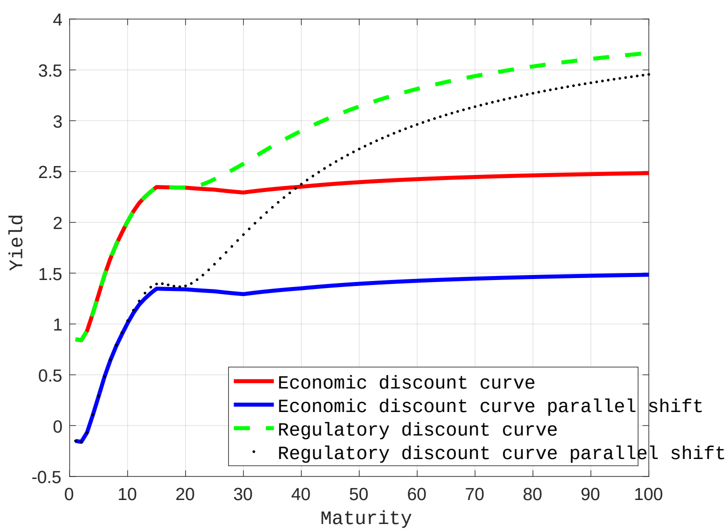


Figure 3. **Regulatory discount curve change 20-year interest rate**

This graph shows the economic discount curve (solid red line) and the regulatory discount curve (solid green line) at implementation of the UFR on September 30, 2012. The graph also shows the economic (dashed blue line) and regulatory (dotted black line) discount curve after a change in the 20-year market interest rate of $\triangle y_t^{(20)} = -0.5\%$.

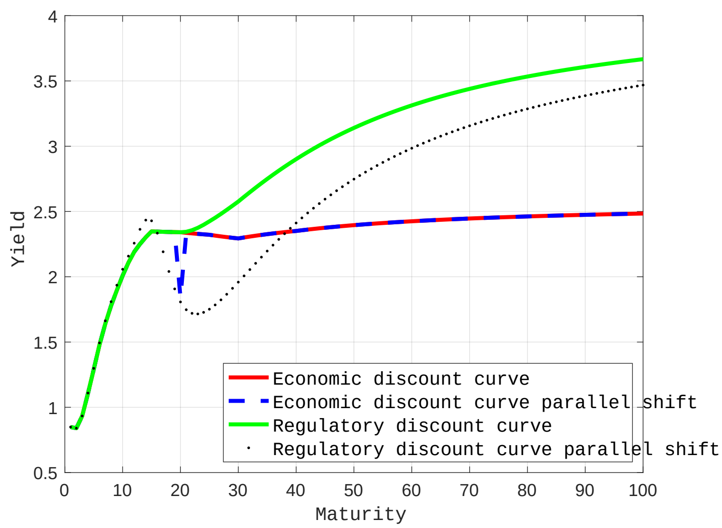


Figure 4. **Cash flows distribution of the liabilities**

This graph shows the (discounted) cash flows distribution of the liabilities for an average pension fund in million euros.

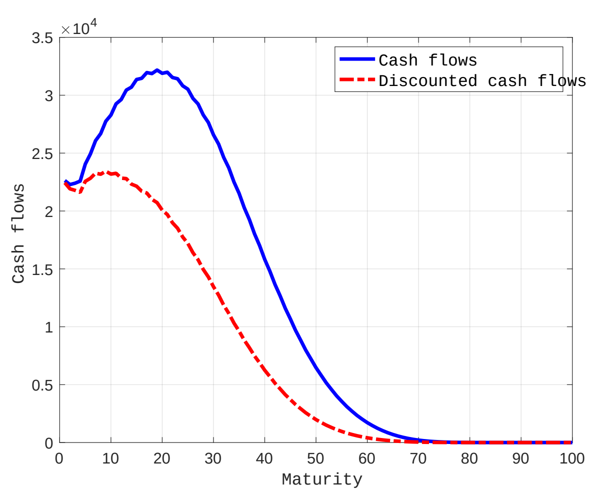


Figure 5. **Long-term bond holdings by P&I type**

This graph shows the average fraction of the bond portfolio that is invested in bonds with a maturity of 30 years or longer for life insurers, non-life insurers, and pension funds over the period 2009q1-2019q1.

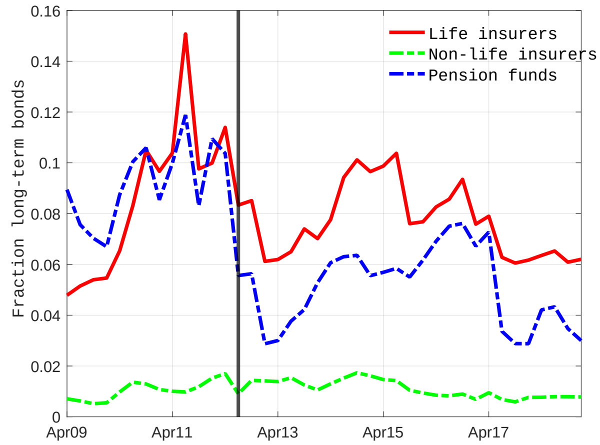


Figure 6. **Implied duration of pension funds' portfolios**

This graph shows the implied duration of the swap portfolio and the duration of the total portfolio of pension funds over the period 2011q4-2017q4. The duration of the swap portfolio is determined as the implied dollar duration of the swaps divided by total pension assets. The duration of the total portfolio equals the sum of the implied duration of the swap portfolio and the duration of the fixed income portfolio times the allocation to fixed income.

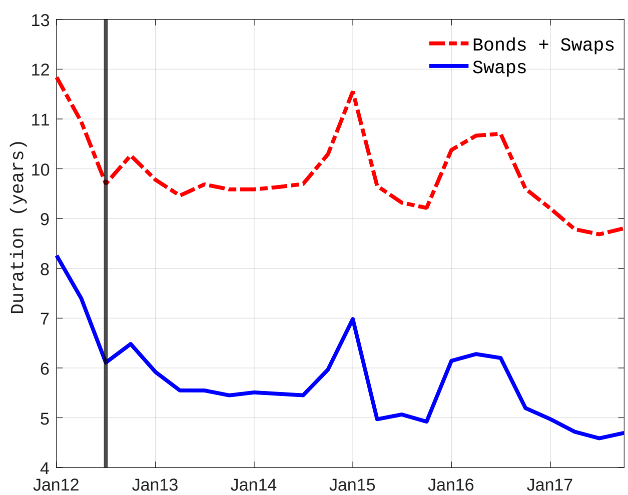
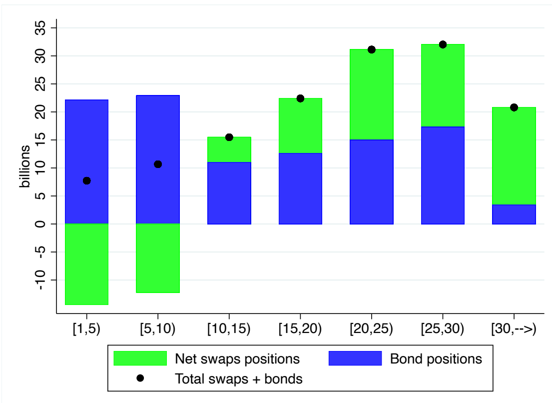
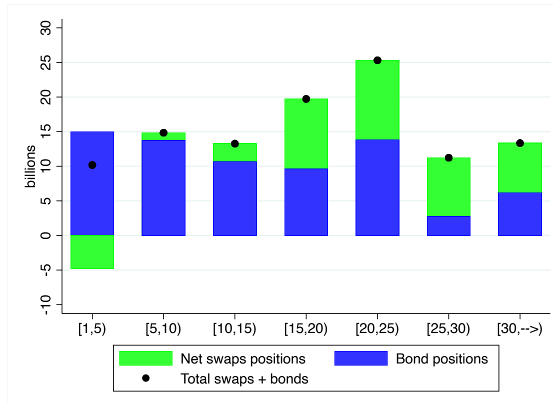


Figure 7. **Net notional maturity buckets: pension funds versus insurers**

This graph shows the net notional exposure towards different maturity buckets for the bond portfolio (blue), swap portfolio (green), and swap and bond portfolio combined (black dot), aggregated across institutions for pension funds (a) and insurers (b) separately. For bonds, the aggregate exposure is based on safe (investment grade) EU government bonds. For swaps, the aggregate exposure is based on Euribor plain vanilla swaps. Calculations are based on 2019q4.



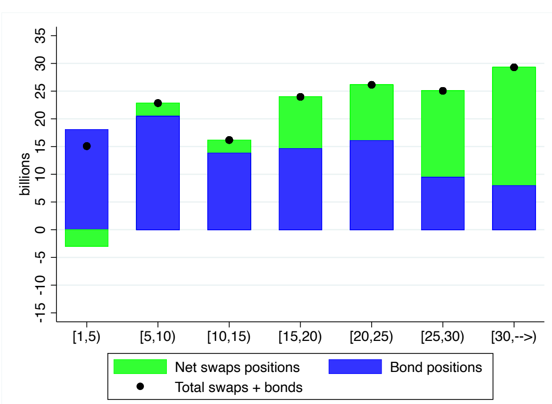
(a) Pension funds



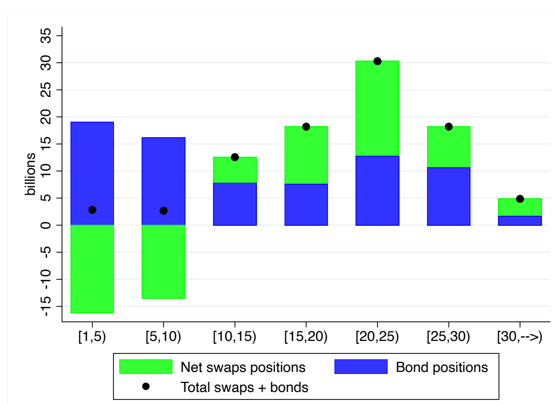
(b) Insurance companies

Figure 8. **Net notional maturity buckets: unconstrained versus constrained P&Is**

This graph shows the net notional exposure towards different maturity buckets for the bond portfolio (blue), swap portfolio (green), and swap and bond portfolio combined (black dot), for constrained and unconstrained P&Is separately. Constrained (unconstrained) P&Is are defined as the ones with funding positions below (above) the median, measured separately for pension funds and insurance companies. For bonds, the aggregate exposure is based on safe (investment grade) EU government bonds. For swaps, the aggregate exposure is based on Euribor plain vanilla swaps. Calculations are based on 2019q4.



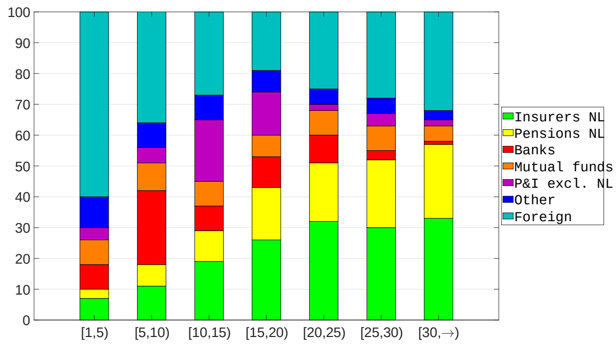
(a) Unconstrained P&Is



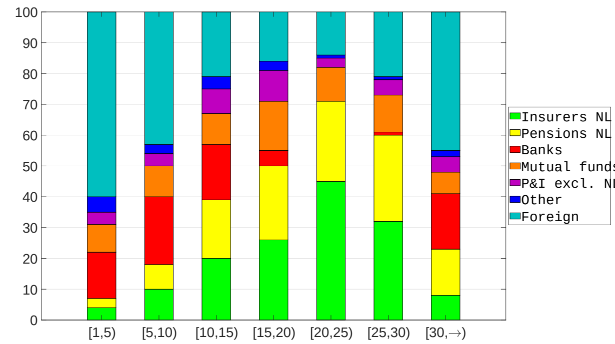
(b) Constrained P&Is

Figure 9. **Weights of investor types in each maturity bucket**

This figure displays the average weights of the investor types (banks, insurance companies, foreign investors, mutual funds, pension funds, and other investors) that held Dutch debt the year prior to the regulatory change 2011q1-2012q1 (Panel a) and the year after the regulatory change 2012q3-2013q3 (Panel b). The banks, mutual funds, an other investor types are at the euro area level. Dutch pension funds, Dutch insurance companies and the P&I sector in the euro area excluding the Netherlands are separately reported. The fraction of foreign investors is determined as the fraction of total amount outstanding that is not held by euro area investors.



(a) Investor weights prior to the UFR



(b) Investor weights after the UFR

Figure 10. **Calibration of the effect of the regulatory change on the yield curve**

This graph depicts the actual yield curve prior to the regulatory change (black line), the calibrated yield curve at the implementation of the UFR when arbitrageur wealth is assumed to be 7.07% of total Dutch debt (red dashed line), and the calibrated yield curve at the implementation of the UFR when arbitrageur wealth is assumed to be 29.5% of total Dutch debt (blue dotted line).

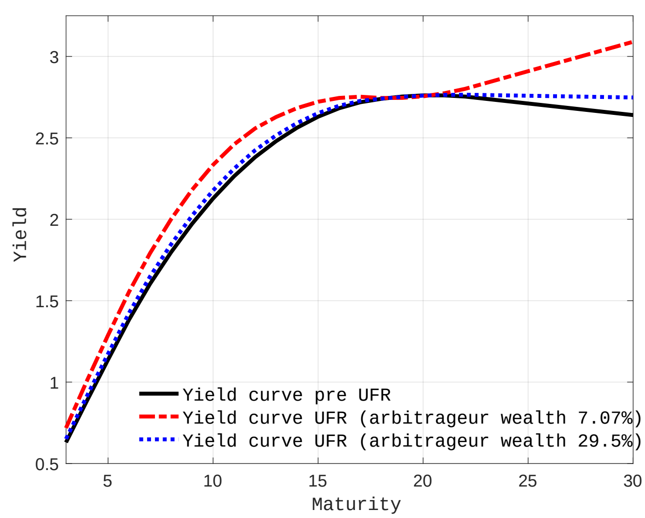


Table 1. **Economic versus regulatory value of the liabilities**: This table shows the value of the liabilities using the economic discount curve versus a discount curve based on the UFR for an average P&I in my sample on September 30, 2012. Panel A shows the sensitivity of the liabilities towards a parallel shift in interest rates and Panel B shows the sensitivity towards the 20 year interest rate. The liability values are computed for all projected cash flows and for cash flows with maturities beyond 20 years in isolation. The relative change computes the percentage point drop in the liability value as a result of the new regulatory discount curve based on the UFR. The values are in million euros.

Panel A: Sensitivity parallel shift interest rates

	economic	**UFR**	**relative change**
All maturities			
Discounted value liabilities	16,360	15,696	−4.23
Discounted value liabilities $\triangle y_t = -1$	19,878	18,433	−7.27
Change value liabilities $\triangle y_t = -1$	3,518	2,737	−22.20
Maturities beyond 20 years			
Discounted value liabilities	6,694	6,030	−9.92
Discounted value liabilities $\triangle y_t = -1$	9,155	7,711	−15.77
Change value liabilities $\triangle y_t = -1$	2,461	1,680	−31.74

Panel B: Sensitivity change 20 year interest rate

	economic	**UFR**	**relative change**
All maturities			
Discounted value liabilities	16,360	15,696	−4.23
Discounted value liabilities $\triangle y_t^{(20)} = -0.5$	16,405	16,918	+3.13
Change value liabilities $\triangle y_t^{(20)} = -0.5$	45	1,222	+2,615.56
Maturities beyond 20 years			
Discounted value liabilities	6,694	6,030	−9.92
Discounted value liabilities $\triangle y_t^{(20)} = -0.5$	6,694	7,164	+7.02
Change value liabilities $\triangle y_t^{(20)} = -0.5$	0	1,134	.

Table 2. **Summary statistics**: This table shows summary statistics on the AUM for each investor type (Panel A), the asset allocation for each investor type (Panel B), and the liability information for the P&I sector (Panel C). In particular, I report the AUM of all assets, AUM of directly reported assets, allocation to government bonds, allocation to corporate bonds, allocation to stocks, bond duration, liability duration, and the solvency positions measured by the funding ratio. The asset allocation and funding ratios are in percentage points, AUM in million euro, bond and liability duration in years. The cross-sectional mean, standard deviation, and median are reported. Equity mutual funds are excluded from the sample.

Panel A: AUM

All assets	mean	std.dev.	p50	**Directly reported**	mean	std.dev.	p50
Banks	16,211	24,748	3,412	Banks	16,101	24,625	3,394
Life insurers	25,669	20,619	25,964	Life insurers	18,963	15,933	18,217
Non-life insurers	1,516	1,392	961	Non-life insurers	1,329	1,366	741
Mutual funds	739	1,467	412	Mutual funds	669	1,271	376
Pension funds	17,664	43,864	6,259	Pension funds	14,845	40,246	4,000

Panel B: Asset allocation

Government bonds	mean	std.dev.	p50	**Corporate bonds**	mean	std.dev.	p50
Banks	23	20	21	Banks	67	28	70
Life insurers	49	13	49	Life insurers	33	12	31
Non-life insurers	45	20	45	Non-life insurers	35	23	35
Mutual funds	46	38	53	Mutual funds	35	40	14
Pension funds	38	17	34	Pension funds	21	13	20

Stocks	mean	std.dev.	p50	**Bond duration**	mean	std.dev.	p50
Banks	7	19	0	Banks	1.78	1.42	1.62
Life insurers	10	10	7	Life insurers	8.43	2.29	8.20
Non-life insurers	14	20	4	Non-life insurers	4.64	1.65	4.80
Mutual funds	13	30	0	Mutual funds	4.86	3.27	5.18
Pension funds	34	17	37	Pension funds	7.32	2.21	7.04

Panel C: Liability information P&Is

Liability duration	mean	std.dev.	p50	**Funding ratio**	mean	std.dev.	p50
Life insurers	11.80	3.96	12.63	Life insurers	111	5	109
Non-life insurers	4.21	2.62	3.44	Non-life insurers	112	7	110
Pension funds	17.99	3.02	17.80	Pension funds	109	12	108

Table 3. **Long-term bond holdings and the regulatory discount curve**: This table presents the results of the main regression described in Equation (14), with the dependent variable equal to the fraction of the P&I's bond portfolio invested in a certain maturity bucket, UFR equal to 1 as of 2012q2 and zero otherwise, D^L_{2011q2} the duration of the liabilities as of 2011q2, and controls include the lagged liability duration, the lagged inverse of the funding ratio, the lagged inverse of the funding ratio interacted with a dummy that indicates pension funds, and the log of size (AUM). Column (1) and (2) show the results for bond holdings with a maturity of 30 years or longer, column (3) and (4) for maturities between 15 and 25 years, and column (5) and (6) for maturities shorter than 15 years. Standard errors are clustered at the investor level and the corresponding t-statistics are in brackets; $^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$.

	Holdings **$T \geq 30$**		Holdings **$15 < T \leq 25$**		Holdings **$T \leq 15$**	
	(1)	(2)	(3)	(4)	(5)	(6)
UFR	0.0012		-0.008		0.0107	
	[0.32]		[-1.07]		[0.62]	
D^L_{2011q2}	0.0031***		0.0024		-0.0036	
	[4.12]		[1.33]		[-1.37]	
D^L_{2011q2}×UFR	-0.0014***	-0.0014***	0.0019***	0.0026***	0.0006	0.0001
	[-4.07]	[-5.08]	[3.38]	[6.29]	[0.49]	[0.06]
D^L_{t-1}	-0.0011	0.0038***	0.0002	0.0032	0.0046*	-0.0176***
	[-1.61]	[4.77]	[0.13]	[1.43]	[1.94]	[-7.54]
FR^{-1}_{t-1}	0.0252	0.0315	-0.0273	-0.0406	-0.2033***	-0.1290**
	[0.87]	[1.24]	[-0.55]	[-0.98]	[-2.58]	[-1.99]
$FR^{-1}_{t-1}\times$ Pension funds	-0.018	0.0229	-0.0732	-0.0349	0.1478*	0.0391
	[-0.53]	[0.70]	[-1.43]	[-0.75]	[1.71]	[0.54]
Log size	0.0085***	-0.0163	0.0097**	-0.0177	-0.0275***	0.0665**
	[3.33]	[-1.32]	[2.52]	[-1.42]	[-3.58]	[2.09]
Life insurance	0.0460***		0.0554***		-0.1016***	
	[9.56]		[6.42]		[-6.36]	
Pension funds	0.0286		0.0812*		-0.2166***	
	[0.93]		[1.67]		[-2.70]	
Fund FE	No	Yes	No	Yes	No	Yes
Time FE	No	Yes	No	Yes	No	Yes
Observations	2274	2274	2274	2274	2274	2274
adj. R-squared	0.1514	0.6242	0.1404	0.6662	0.0652	0.7182

Table 4. **Asset allocation and the regulatory discount curve**: This table presents the results of the regression described in Equation (15), with the dependent variable equal to a measure of P&I's risky asset allocation, UFR equal to 1 as of 2012q2 and zero otherwise, D^L_{2011q2} the duration of the liabilities as of 2011q2, and controls include the lagged liability duration, the lagged inverse of the funding ratio, the lagged inverse of the funding ratio interacted with a dummy that indicates pension funds, and the log of size (AUM). Column (1) shows the results for the equity allocation, column (2) for the corporate bond allocation, column (3) for the corporate bond distance-to-default measure (DTD), column (4) for the government bond allocation, column (5) for government bond credit risk, and column (6) for the high yield government bond allocation. Standard errors are clustered at the investor level and the corresponding t-statistics are in brackets; $^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$.

	Equity	**Corporate bonds**		**Government bonds**		
	Allocation	Allocation	DTD	Allocation	Credit rating	High yield
	(1)	(2)	(3)	(4)	(5)	(6)
$D^L_{2011q2} \times$ UFR	0.0021**	-0.0020**	0.0311	-0.0001	-0.0418**	0.0025***
	[2.25]	[-2.37]	[0.87]	[-0.15]	[-2.36]	[2.69]
D^L_{t-1}	-0.001	0.0016	0.1689**	-0.0009	0.0468	0.0030***
	[-0.55]	[0.66]	[2.02]	[-0.38]	[1.20]	[2.80]
FR^{-1}_{t-1}	0.032	0.2246***	-3.9547	-0.2612***	-1.0978	-0.0702**
	[0.58]	[3.12]	[-1.54]	[-4.08]	[-0.76]	[-2.57]
$FR^{-1}_{t-1} \times$ Pension funds	-0.0468	-0.0691	1.8776	0.1333*	-4.0496**	0.0023
	[-0.73]	[-0.87]	[0.57]	[1.72]	[-2.56]	[0.07]
Log size	0.1098***	-0.021	-3.1733***	-0.0231	2.3278***	-0.0735*
	[3.48]	[-0.78]	[-3.05]	[-0.66]	[3.42]	[-1.92]
Fund FE	Yes	Yes	Yes	Yes	Yes	Yes
Time FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	2274	2274	2254	2274	2269	2269
adj. R-squared	0.847	0.7685	0.6842	0.7296	0.5862	0.3465

Table 5. **Long-term bond holdings and constraints**: This table present the results of the regression described in Equation (16), with the dependent variable equal to the fraction of the P&I's bond portfolio invested in a certain maturity bucket, UFR equal to 1 as of 2012q2 and zero otherwise, D^L_{2011q2} the duration of the liabilities as of 2011q2, and FR^{-1}_{2011q2} the inverse of the funding ratio minus 1 as of 2011q2. Controls include the lagged liability duration, the lagged inverse of the funding ratio, the lagged inverse of the funding ratio interacted with a dummy that indicates pension funds, and the log of size (AUM). P&I type fixed effects include dummies indicating pension funds, life insurers, or non-life insurers. Column (1) and (2) show the results for bond holdings with a maturity of 30 years or longer, column (3) and (4) for maturities between 15 and 25 years, and column (5) and (6) for maturities shorter than 15 years. Standard errors are clustered at the investor level and the corresponding t-statistics are in brackets; $^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$.

	Holdings $\boldsymbol{T \geq 30}$		Holdings $\boldsymbol{15 < T \leq 25}$		Holdings $\boldsymbol{T \leq 15}$	
	(1)	(2)	(3)	(4)	(5)	(6)
UFR	-0.004		-0.0432**		0.0205	
	[-0.31]		[-2.42]		[0.45]	
D^L_{2011q2}	0.0046***		0.0042**		-0.0059*	
	[3.99]		[2.11]		[-1.65]	
FR^{-1}_{2011q2}	-0.1713		-0.4536***		0.3814	
	[-1.56]		[-2.71]		[1.13]	
$D^L_{2011q2} \times FR^{-1}_{2011q2}$	0.0234**		0.0245**		-0.0486**	
	[2.57]		[2.28]		[-2.04]	
$D^L_{2011q2} \times$ UFR	-0.0020*	-0.0025***	0.0050***	0.0043***	0.0002	0.0002
	[-1.75]	[-3.60]	[4.12]	[4.93]	[0.05]	[0.09]
$FR^{-1}_{2011q2} \times$ UFR	-0.0461	0.1337*	-0.3478*	-0.061	0.1344	-0.2294
	[-0.39]	[1.84]	[-1.79]	[-0.48]	[0.36]	[-1.05]
$D^L_{2011q2} \times FR^{-1}_{2011q2} \times$ UFR	-0.0042	-0.0115**	0.0316**	0.0165**	-0.0107	0.0017
	[-0.43]	[-2.02]	[2.49]	[2.07]	[-0.41]	[0.13]
Controls	Yes	Yes	Yes	Yes	Yes	Yes
P&I type FE	Yes	No	Yes	No	Yes	No
Fund FE	No	Yes	No	Yes	No	Yes
Time FE	No	Yes	No	Yes	No	Yes
Observations	2274	2274	2274	2274	2274	2274
adj. R-squared	0.1739	0.6253	0.1614	0.6699	0.0852	0.7193

Table 6. **Instrument for every maturity bucket**: This table shows the value of the instrument for each maturity bucket used in the instrumental variable approach. The instrument is constructed as the average weight assigned to the UFR for each maturity bucket, minus the average weight assigned to the 20-year interest rate for the maturities 20-40 years, equally distributed over the $(15, 20]$ and $(20, 25]$ maturity buckets. An overview of the weights for each separate maturity is given in Table A1.

	$(1, 5]$	$(5, 10]$	$(10, 15]$	$(15, 20]$	$(20, 25]$	$(25, 30]$	$(30, \infty)$
$\xi(h)$	0	0	0	-0.41	-0.15	0.58	0.91

Table 7. **Demand system**: This table shows the regression results of the demand system described in Equation (21). The first column shows the first stage regression for the foreign investors. The instrument $z_t(h)$ equals the weights assigned to the UFR for each maturity bucket h interacted with a dummy that equals one after implementation of the UFR. Bond characteristics $x_t(h)$ include the average bond duration, convexity, coupon, and the log of AUM outstanding. The outside asset O_{it} is proxied by the 10-year German yield and initial holdings are added as control to capture time-invariant omitted characteristics. The standard errors are clustered by quarter and the corresponding t-statistics are in brackets; $^*p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$.

	$y_t(h)$	Holdings Foreign	Holdings Bank	Holdings MF	Holdings P&I excl. NL	Holdings Other
$y_t(h)$		0.5419**	1.4261***	0.3968*	-0.0261	0.2175
		[2.26]	[3.09]	[1.69]	[-0.06]	[1.43]
$z_t(h)$	0.2971***					
	[5.85]					
Duration	0.2821***	-0.2853***	-1.5016***	-0.0706	0.0793	-0.3585**
	[37.95]	[-4.13]	[-3.51]	[-1.08]	[0.66]	[-2.40]
Convexity	-0.0087***	0.0087***	0.0368***	0.0016	-0.0048*	0.0031
	[-26.77]	[4.56]	[3.62]	[0.86]	[-1.65]	[0.76]
Coupon	-0.0314**	-0.0801***	-0.0601	-0.1898***	-0.0059	-0.0018
	[-2.42]	[-3.80]	[-0.57]	[-12.07]	[-0.18]	[-0.06]
AUM outstanding	-0.1061***	1.1957***	0.9240**	0.7053***	0.2944***	0.6922***
	[-3.42]	[16.27]	[2.18]	[12.91]	[5.76]	[6.38]
10-year German yield	1.0560***	-0.7087**	-1.7336***	-0.366	-0.078	0.0829
	[21.93]	[-2.51]	[-2.98]	[-1.43]	[-0.15]	[0.13]
Initial holdings	0.0102	-0.042	0.1102	0.1433**	0.3491***	-0.3762*
	[0.44]	[-0.69]	[0.27]	[2.24]	[3.61]	[-1.92]
Observations	245	245	245	245	245	245
adj. R-squared	0.96					

Table 8. **Price elasticity of demand**: This table shows the price elasticity of demand, computed as in Equation (23) for each investor type, maturity bucket h, and quarter t. The median, standard deviation, minimum, and maximum over time are given. The total elasticity is the weighted median elasticity, using the weights of each sector defined in the last column.

	obs	median	std.dev.	min	max	weights
Banks euro	245	10.70	15.24	5.66	57.55	16
Foreign investors	245	3.56	2.04	1.79	9.80	55
Mutual funds euro	245	1.65	1.02	1.31	4.79	11
P&I euro (except NL)	245	0.84	0.25	0.08	0.92	7
Other euro	245	1.99	1.56	1.48	6.80	10
Total		**4.11**				100

Table 9. **Effects of the UFR at the European level**: This table shows the effects of the UFR on yield spreads for a panel of European countries over the period 2006-2020 (annual). The UFR equals one as of the announcement of the UFR as part of the Solvency II regulation in August, 2015, except for the countries Denmark, the Netherlands, and Sweden where the dummy equals one as of June 2012, July 2012, and February 2013, respectively. Size IC market equals the size of the insurance market relative to debt in 2015. Controls include the 10-2y government bond spread, debt-to-GDP ratio, CDS spread, and age of the population. Standard errors are clustered at the country level and the corresponding t-statistics are in brackets; $^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$.

	Spread 30-20y		**Spread 20-10y**		**Spread 30-10y**	
	(1)	(2)	(3)	(4)	(5)	(6)
UFR	0.1278***		0.1879***		0.3157***	
	[3.34]		[2.60]		[3.56]	
size IC market	-0.0596***		0.0744		0.0148	
	[-2.62]		[1.50]		[0.26]	
size IC market × UFR	0.0511*	0.0656***	-0.1043*	-0.1052**	-0.0532	-0.0396
	[1.81]	[2.63]	[-1.71]	[-2.27]	[-0.75]	[-0.71]
10-2y spread	0.0477***	0.0508***	-0.012	-0.0216	0.0357	0.0291
	[7.06]	[9.36]	[-0.66]	[-0.94]	[1.54]	[1.05]
Debt to GDP	0.0007	0.0017	0.0031***	0.0027	0.0038***	0.0045
	[1.55]	[1.60]	[4.00]	[1.22]	[3.61]	[1.60]
CDS	-0.0005***	-0.0004***	-0.0009***	-0.0009**	-0.0013***	-0.0013***
	[-4.23]	[-4.09]	[-3.38]	[-2.57]	[-3.79]	[-2.93]
Age	-0.0019	-0.0336	0.011	0.0234	0.0091	-0.0102
	[-0.37]	[-1.50]	[1.09]	[0.82]	[0.84]	[-0.32]
Country FE	No	Yes	No	Yes	No	Yes
Time FE	No	Yes	No	Yes	No	Yes
Observations	286	286	286	286	286	286
adj. R-squared	0.829	0.865	0.416	0.525	0.705	0.752

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Appendix A Additional tables

Table A1. **Weights UFR for the regulatory discount curve**: This table shows the weights assigned to the UFR to compute the regulatory discount curve. The weights are fixed and derived using the Smith-Wilson technique. The weights beyond 60 years are equal to 1.

time-to-maturity	weight	time-to-maturity	weight
21	0.086	41	0.903
22	0.186	42	0.914
23	0.274	43	0.923
24	0.351	44	0.932
25	0.420	45	0.940
26	0.481	46	0.947
27	0.536	47	0.954
28	0.584	48	0.960
29	0.628	49	0.965
30	0.666	50	0.970
31	0.701	51	0.974
32	0.732	52	0.978
33	0.760	53	0.982
34	0.785	54	0.985
35	0.808	55	0.988
36	0.828	56	0.990
37	0.846	57	0.993
38	0.863	58	0.995
39	0.878	59	0.997
40	0.891	60	0.998

Table A2. **Long-term bond holdings and the regulatory discount curve 2009q1-2014q3**: This table presents the results of the main regression described in Equation (14) for the sample period 2009q1-2014q3, with the dependent variable equal to the fraction of the P&I's bond portfolio invested in a certain maturity bucket, UFR equal to 1 as of 2012q2 and zero otherwise, D^L_{2011q2} the duration of the liabilities as of 2011q2, and controls include the lagged liability duration, the lagged inverse of the funding ratio, the lagged inverse of the funding ratio interacted with a dummy that indicates pension funds, and the log of size (AUM). Column (1) and (2) show the results for bond holdings with a maturity of 30 years or longer, column (3) and (4) for maturities between 15 and 25 years, and column (5) and (6) for maturities shorter than 15 years. Standard errors are clustered at the investor level and the corresponding t-statistics are in brackets; $^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$.

	Holdings $\boldsymbol{T \geq 30}$		Holdings $\boldsymbol{15 < T \leq 25}$		Holdings $\boldsymbol{T \leq 15}$	
	(1)	(2)	(3)	(4)	(5)	(6)
UFR	0.0068		-0.0174**		0.019	
	[1.51]		[-2.00]		[0.90]	
D^L_{2011q2}	-0.0018		0.0026		-0.004	
	[-1.32]		[0.73]		[-0.82]	
$D^L_{2011q2}\times$ UFR	-0.0017***	-0.0016***	0.0026***	0.0029***	-0.0001	-0.0009
	[-4.10]	[-5.71]	[3.76]	[7.60]	[-0.06]	[-1.07]
D^L_{t-1}	0.0041***	0.0034***	0	0.0022	0.0034	-0.0125***
	[2.85]	[2.67]	[-0.01]	[0.63]	[0.72]	[-4.21]
FR^{-1}_{t-1}	0.0582	-0.0071	-0.0496	0.0043	-0.1821*	0.0165
	[1.58]	[-0.21]	[-0.89]	[0.08]	[-1.91]	[0.22]
$FR^{-1}_{t-1}\times$ Pension funds	-0.0306	-0.0025	-0.0683	-0.026	0.0868	-0.0373
	[-0.66]	[-0.05]	[-1.12]	[-0.45]	[0.79]	[-0.44]
Log size	0.0125***	-0.0231	0.0193***	-0.0074	-0.0418***	0.0743*
	[2.96]	[-1.31]	[3.33]	[-0.47]	[-3.51]	[1.80]
Life insurance	0.0421***		0.0355***		-0.0592***	
	[6.04]		[3.14]		[-2.73]	
Pension funds	0.035		0.0697		-0.1233	
	[0.83]		[1.21]		[-1.21]	
Fund FE	No	Yes	No	Yes	No	Yes
Time FE	No	Yes	No	Yes	No	Yes
Observations	1300	1300	1300	1300	1300	1300
adj. R-squared	0.1421	0.669	0.1316	0.7058	0.0598	0.771

Table A3. **Asset allocation and the regulatory discount curve 2009q1-2014q3**: This table presents the results of the regression described in Equation (15) for the sample period 2009q1-2014q3, with the dependent variable equal to a measure of P&I's risky asset allocation, UFR equal to 1 as of 2012q2 and zero otherwise, D^L_{2011q2} the duration of the liabilities as of 2011q2, and controls include the lagged liability duration, the lagged inverse of the funding ratio, the lagged inverse of the funding ratio interacted with a dummy that indicates pension funds, and the log of size (AUM). Column (1) shows the results for the equity allocation, column (2) for the corporate bond allocation, column (3) for the corporate bond distance-to-default measure (DTD), column (4) for the government bond allocation, column (5) for government bond credit risk, and column (6) for the high yield government bond allocation. Standard errors are clustered at the investor level and the corresponding t-statistics are in brackets; $^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$.

	Equity	**Corporate bonds**		**Government bonds**		
	Allocation	Allocation	DTD	Allocation	Credit rating	High yield
	(1)	(2)	(3)	(4)	(5)	(6)
$D^L_{2011q2} \times$ UFR	0.0029***	-0.0022***	-0.0031	-0.0014	-0.0268*	0.0016**
	[3.63]	[-2.70]	[-0.16]	[-1.50]	[-1.78]	[2.11]
D^L_{t-1}	0.0012	-0.0058	-0.0907	0.0006	0.0689	-0.0002
	[0.61]	[-1.43]	[-0.70]	[0.16]	[1.18]	[-0.17]
FR^{-1}_{t-1}	-0.0453	0.2082***	-3.5332*	-0.1609**	-1.7425	-0.0439
	[-0.80]	[2.59]	[-1.97]	[-2.11]	[-1.14]	[-1.21]
$FR^{-1}_{t-1} \times$ Pension funds	0.0267	-0.0305	-0.1788	-0.0359	-3.8266**	0.0312
	[0.41]	[-0.36]	[-0.08]	[-0.41]	[-2.11]	[0.73]
Log size	-0.0191	-0.0369	-2.5771	0.1003**	4.0878***	-0.1469***
	[-0.52]	[-1.09]	[-1.25]	[2.12]	[3.65]	[-2.91]
Fund FE	Yes	Yes	Yes	Yes	Yes	Yes
Time FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	1300	1300	1291	1300	1295	1295
adj. R-squared	0.8997	0.7944	0.8244	0.7935	0.6457	0.3481

Table A4. **Long-term bond holdings and constraints 2009q1-2014q3**: This table presents the results of the regression described in Equation (16) for the sample period 2009q1-2014q3, with the dependent variable equal to the fraction of the P&I's bond portfolio invested in a certain maturity bucket, UFR equal to 1 as of 2012q2 and zero otherwise, D^L_{2011q2} the duration of the liabilities as of 2011q2, and FR^{-1}_{2011q2} the inverse of the funding ratio minus 1 as of 2011q2. Controls include the lagged liability duration, the lagged inverse of the funding ratio, the lagged inverse of the funding ratio interacted with a dummy that indicates pension funds, and the log of size (AUM). P&I type fixed effects include dummies indicating pension funds, life insurers, or non-life insurers. Column (1) and (2) show the results for bond holdings with a maturity of 30 years or longer, column (3) and (4) for maturities between 15 and 25 years, and column (5) and (6) for maturities shorter than 15 years. Standard errors are clustered at the investor level and the corresponding t-statistics are in brackets; $^*p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$.

	Holdings **$T \geq 30$**		Holdings **$15 < T \leq 25$**		Holdings **$T \leq 15$**	
	(1)	(2)	(3)	(4)	(5)	(6)
UFR	0.0026		-0.0508**		0.0547	
	[0.17]		[-2.31]		[0.93]	
D^L_{2011q2}	0		0.0044		-0.0069	
	[-0.02]		[1.23]		[-1.26]	
FR^{-1}_{2011q2}	-0.2348**		-0.5202***		0.446	
	[-2.03]		[-3.10]		[1.26]	
$D^L_{2011q2} \times FR^{-1}_{2011q2}$	0.0277***		0.0241**		-0.0467*	
	[2.94]		[2.22]		[-1.88]	
$D^L_{2011q2} \times$ UFR	-0.0023*	-0.0026***	0.0051***	0.0047***	-0.0019	-0.0019
	[-1.76]	[-3.52]	[3.32]	[5.15]	[-0.47]	[-1.02]
$FR^{-1}_{2011q2} \times$ UFR	-0.0343	0.0734	-0.3147	-0.1975	0.3595	0.1419
	[-0.25]	[0.99]	[-1.35]	[-1.49]	[0.77]	[0.61]
$D^L_{2011q2} \times FR^{-1}_{2011q2} \times$ UFR	-0.0054	-0.0103**	0.0243*	0.0179**	-0.0211	-0.0104
	[-0.48]	[-1.97]	[1.66]	[2.09]	[-0.65]	[-0.73]
Controls	Yes	Yes	Yes	Yes	Yes	Yes
P&I type FE	Yes	No	Yes	No	Yes	No
Fund FE	No	Yes	No	Yes	No	Yes
Time FE	No	Yes	No	Yes	No	Yes
Observations	1300	1300	1300	1300	1300	1300
adj. R-squared	0.1619	0.6711	0.1442	0.7066	0.0675	0.7707

Table A5. **Long-term bond holdings and the regulatory discount curve at the security level**: This table presents the results of the regression described in Equation (17), where the dependent variable is the weight assigned to bond s for fund i at time t, with UFR equal to 1 as of 2012q2 and zero otherwise, D^L_{2011q2} the duration of the liabilities as of 2011q2, $\mathbb{1}^{maturity \geq 30}$ an indicator variable that equals one if the time to maturity of bond s at time t is larger or equal to 30 years, and $\mathbb{1}^{maturity \approx 20}$ an indicator variable that equals one if the time to maturity of bond s at time t is between 15 and 25 years. The first three columns show the results for all bonds and the last three columns for safe European Union (EU) bonds. Standard errors are clustered at the security level and the corresponding t-statistics are in brackets; $^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$.

	All bonds			**Investment grade EU bonds**		
	(1)	(2)	(3)	(4)	(5)	(6)
$D^L_{2011q2} \times \mathbb{1}^{maturity \geq 30} \times$ UFR	-0.0006***	-0.0026***	-0.0014***	-0.0138***	-0.0346***	-0.0110**
	[-4.41]	[-5.56]	[-2.90]	[-5.09]	[-6.01]	[-2.16]
$D^L_{2011q2} \times \mathbb{1}^{maturity \approx 20} \times$ UFR	0.0003**	0.0012***	0.0021***	0.0029*	0.0072**	0.0139***
	[2.27]	[3.04]	[5.12]	[1.82]	[2.36]	[4.47]
Time FE	Yes	No	No	Yes	No	No
Fund-security FE	Yes	Yes	Yes	Yes	Yes	Yes
Security-time FE	No	Yes	Yes	No	Yes	Yes
Fund-time FE	No	No	Yes	No	No	Yes
Observations	2,126,974	1,859,566	1,859,566	235,479	225,998	225,994
R-squared	0.8384	0.8281	0.8377	0.7488	0.7454	0.7695

Table A6. **Long-term bond holdings and constraints at the security level**: This table presents the results of the regression described in Equation (18), where the dependent variable is the weight assigned to bond s for fund i at time t, with UFR equal to 1 as of 2012q2 and zero otherwise, D^L_{2011q2} the duration of the liabilities as of 2011q2, FR^{-1}_{2011q2} the inverse of the funding ratio minus 1 as of 2011q2, $\mathbb{1}^{maturity\geq 30}$ an indicator variable that equals one if the time to maturity of bond s at time t is larger or equal to 30 years, and $\mathbb{1}^{maturity\approx 20}$ an indicator variable that equals one if the time to maturity of bond s at time t is between 15 and 25 years. The first three columns show the results for all bonds and the last three columns for safe European Union (EU) bonds. Standard errors are clustered at the security level and the corresponding t-statistics are in brackets; $^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$.

	All bonds			**Investment grade EU bonds**		
	(1)	(2)	(3)	(4)	(5)	(6)
$D^L_{2011q2} \times \text{FR}^{-1}_{2011q2} \times \mathbb{1}^{maturity\geq 30} \times$ UFR	-0.0007***	-0.0018***	-0.0009**	-0.0133***	-0.0223***	-0.0078*
	[-4.38]	[-4.27]	[-2.06]	[-4.63]	[-3.98]	[-1.66]
$D^L_{2011q2} \times \text{FR}^{-1}_{2011q2} \times \mathbb{1}^{maturity\approx 20} \times$ UFR	0.0003**	0.0014***	0.0020***	0.0044***	0.0164***	0.0169***
	[2.42]	[3.75]	[5.18]	[2.66]	[5.32]	[5.35]
Time FE	Yes	No	No	Yes	No	No
Fund-security FE	Yes	Yes	Yes	Yes	Yes	Yes
Security-time FE	No	Yes	Yes	No	Yes	Yes
Fund-time FE	No	No	Yes	No	No	Yes
Observations	2,084,581	1,817,454	1,817,454	228,378	218,891	218,887
R-squared	0.8365	0.8254	0.8348	0.745	0.7409	0.7651

Table A7. **Effects of the UFR at the European level - alternative measure**: This table shows the effects of the UFR on yield spreads for a panel of European countries over the period 2006-2020 (annual). The countries included are: Austria, Belgium, Bulgaria, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Netherlands, Norway, Poland, Portugal, Slovakia, Spain, Sweden, and the UK. The UFR equals one as of the announcement of the UFR as part of the Solvency II regulation in August, 2015, except for the countries Denmark, the Netherlands, and Sweden where the dummy equals one as of June 2012, July 2012, and February 2013, respectively. Size IC market equals the size of the insurance market relative to debt in 2015, multiplied by the liability duration. Controls include the 10-2y government bond spread, the debt-to-GDP ratio, the CDS spread, and the age of the population measured by the fraction of the elderly relative to the total population. Standard errors are clustered at the country level and the corresponding t-statistics are in brackets; $^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$.

	Spread 30-20y		**Spread 20-10y**		**Spread 30-10y**	
	(1)	(2)	(3)	(4)	(5)	(6)
UFR	0.1291***		0.1801***		0.3092***	
	[3.55]		[2.63]		[3.66]	
size IC market	-0.0039***		0.0042		0.0003	
	[-2.82]		[1.41]		[0.09]	
size IC market × UFR	0.0032**	0.0038***	-0.0060*	-0.0066**	-0.0027	-0.0028
	[1.97]	[2.63]	[-1.72]	[-2.42]	[-0.69]	[-0.87]
10-2y spread	0.0477***	0.0507***	-0.012	-0.0215	0.0357	0.0292
	[7.02]	[9.27]	[-0.66]	[-0.94]	[1.54]	[1.05]
Debt to GDP	0.0006	0.0018	0.0031***	0.0026	0.0037***	0.0044
	[1.37]	[1.60]	[4.00]	[1.17]	[3.55]	[1.55]
CDS	-0.0005***	-0.0004***	-0.0009***	-0.0009**	-0.0013***	-0.0013***
	[-4.20]	[-4.06]	[-3.39]	[-2.57]	[-3.79]	[-2.93]
Age	-0.0006	-0.0333	0.0099	0.0227	0.0093	-0.0106
	[-0.11]	[-1.49]	[0.96]	[0.80]	[0.84]	[-0.34]
Country FE	No	Yes	No	Yes	No	Yes
Time FE	No	Yes	No	Yes	No	Yes
Observations	286	286	286	286	286	286
adj. R-squared	0.829	0.865	0.416	0.526	0.705	0.752

Appendix B Further details on the UFR

The UFR was initially discussed as part of the Long-Term Guarantee Assessment (LTGA) of the Solvency II regulation. EIOPA proposed the regulatory discount curve based on the UFR method in 2010 and the official announcement of the adoption of the UFR was made in August 2015. There are three important decisions that policymakers have to make when introducing the UFR: the level of the UFR, the point on the curve at which the UFR method starts, and the interpolation method or the convergence path. The initial EIOPA proposals are first discussed in detail.

The UFR was initially set at 4.2 percent which is based on 2 percent expected inflation and a 2.2 percent historical average of the real short interest rate. The expected inflation rate aligns with the ECB's target inflation. The real interest rate is based on a study by Dimson et al. (2002). The point of the curve at which the UFR method starts was set at 20 years and the convergence period at 40 years. The extrapolation method proposed by EIOPA is the Smith-Wilson technique. The Smith-Wilson technique uses the forward rate for the time-to-maturity of 19 to 20 years and the UFR to compute the yield curve. This technique assumes that the convergence parameter that defines how quickly the discount curve converges to the UFR equals $\alpha = 0.1$. Table A1 shows the weights assigned to the UFR that follow from the Smith-Wilson technique, where the weights are fixed and increase in h. Formally the weights equal:

$$w_h = \frac{f_{h-1}^{h,SW} - f_{19}^{20}}{f_{60}^{61,SW} - f_{19}^{20}} \qquad \text{for} \qquad h = 21, ..., 60, \tag{A.1}$$

where $f_{h-1}^{h,SW}$ are the one year forward rates that follow from the Smith-Wilson method.[38]

[38] The Smith-Wilson technique is described in an EIOPA paper: 'QIS 5 Risk-free interest rates – Extrapolation method': eiopa.europa.eu/Publications/QIS/ceiops-paper-extrapolation-risk-free-ratesen-20100802.pdf.

Appendix C Solution to the optimization problem of long-term investors

This appendix solves the optimal portfolio allocation of P&Is. I start with deriving the economic and regulatory liability values, followed by the solution to the optimization problem.

The economic value of the liabilities equals:

$$L^E_{i,t} = \sum_{h=0} \mathrm{CF}_i(h) \exp(-hy^{(h)}_t). \tag{A.2}$$

A first-order Taylor expansion in $hy^{(h)}_t$ results in the following economic value of the liabilities at time $t+1$:

$$\begin{aligned} L^E_{i,t+1} &= \sum_{h=1} \mathrm{CF}_i(h) \exp(-(h-1)y^{(h-1)}_{t+1}) \\ &\approx \sum_{h=1} \mathrm{CF}_i(h) \exp(-hy^{(h)}_t)\Big(1 + y^{(h)}_t - (h-1)(y^{(h-1)}_{t+1} - y^{(h)}_t)\Big) \\ &= \mathbf{a}'_{i,t}(\mathbf{1} + \mathbf{r}^B_{t+1})L^E_{i,t}, \end{aligned} \tag{A.3}$$

The regulatory value of the liabilities equals:

$$L^R_{i,t} = \sum_{h=0} \mathrm{CF}_i(h) \exp\Big(-h\big(\mathbb{1}_{h<20}y^{(h)}_t + \mathbb{1}_{h\geq 20}\{\xi_L(h)y^{(20)}_t + (1-\xi_L(h))UFR\}\big)\Big), \tag{A.4}$$

where UFR is a constant. A first-order Taylor expansion in $hy^{(h)}_t$ for maturities below 20 years and in $hy^{(20)}_t$ for maturities as of 20 years results in the following evolution of the regulatory liability value over time:

$$L^R_{i,t+1} \approx \Big(\mathbb{1}_{h<20}\mathbf{a}'_{i,t}(\mathbf{1} + \mathbf{r}^B_{t+1}) + \mathbb{1}_{h\geq 20}\mathbf{a}'_{i,t}(\mathbf{1} + \boldsymbol{\xi}_L r^{20}_{t+1})\Big)L^R_{i,t}. \tag{A.5}$$

For ease of notation, the proof of the optimization problem is based on a more general form of the regulatory value of the liabilities in Equation (A.5): $L^R_{i,t+1} = \mathbf{a}'_{i,t}(\mathbf{1} + \boldsymbol{\xi}'_L\mathbf{r}^L_{t+1})L^R_{i,t}$, where $\mathbf{r}^L_{t+1}$ is a vector of liability returns that is uncorrelated with the risky asset S and the same length as the set of bonds B. Following the proof below and substituting other forms of the regulatory value of the liabilities automatically leads to the correct specification of the optimal portfolio holdings. The mean-variance optimization problem equals:

$$\begin{aligned} \max_{\mathbf{w}_{i,t}} \quad & \mathbb{E}_{i,t}[u(\frac{A_{i,t+1}}{A_{i,t}} - \frac{L_{i,t+1}}{A_{i,t}})] \\ = \quad & \arg\max_{\mathbf{w}_{i,t}} \mathbb{E}_{i,t}[\frac{A_{i,t+1}}{A_{i,t}}] - \frac{\gamma}{2}\text{Var}_{i,t}[\frac{A_{i,t+1}}{A_{i,t}} - \frac{L^E_{i,t+1}}{A_{i,t}}] - \frac{\lambda(F^R_{i,t})}{2}\text{Var}_{i,t}[\frac{A_{i,t+1}}{A_{i,t}} - \frac{L^R_{i,t+1}}{A_{i,t}}], \end{aligned}$$

subject to

$$\mathbf{w}'_{i,t}\mathbf{1} = w^S_{i,t} + \mathbf{w}^{B\prime}_{i,t}\mathbf{1} \leq 1, \qquad w^S_{i,t}, w^B_{i,t}(h) \geq 0 \quad \forall h.$$

The Lagrange equals:

$$\begin{aligned} \mathcal{L}(\mathbf{w}_{i,t}, \nu_{i,t}, \boldsymbol{\delta}_{i,t}) \; = \; & 1 + r_f + \mathbf{w}'_{i,t}\mathbb{E}_{i,t}[\mathbf{r}_{t+1} - r_f\mathbf{1}] \\ - \; & \frac{\gamma}{2}\Big(\mathbf{w}'_{i,t}\text{Var}_{i,t}[\mathbf{r}_{t+1}]\mathbf{w}_{i,t} + \mathbf{a}'_{i,t}\text{Var}_{i,t}[\mathbf{r}^L_{t+1}]\mathbf{a}_{i,t}\frac{1}{F^E_{i,t}} - 2\mathbf{w}'_{i,t}(\mathbf{a}_{i,t} \circ \text{Cov}_{i,t}[\mathbf{r}^L_{t+1}, \mathbf{r}_{t+1}])\frac{1}{F^E_{i,t}}\Big) \\ - \; & \frac{\lambda(F^R_{i,t})}{2}\Big(\mathbf{w}'_{i,t}\text{Var}_{i,t}[\mathbf{r}_{t+1}]\mathbf{w}_{i,t} + (\mathbf{a}_{i,t} \circ \boldsymbol{\xi}_L)'\text{Var}_{i,t}[\mathbf{r}^L_{t+1}](\mathbf{a}_{i,t} \circ \boldsymbol{\xi}_L)\frac{1}{F^R_{i,t}} \\ - \; & 2\mathbf{w}'_{i,t}(\mathbf{a}_{i,t} \circ \boldsymbol{\xi}_L \circ \text{Cov}_{i,t}[\mathbf{r}^L_{t+1}, \mathbf{r}_{t+1}])\frac{1}{F^R_{i,t}}\Big) + \nu_{i,t}(\mathbf{w}'_{i,t}\mathbf{1} - 1) + \boldsymbol{\delta}'_{i,t}\mathbf{w}_{i,t}. \end{aligned} \tag{A.6}$$

Taking the derivative with respect to w^S_t, w^B_t, and $\nu_{i,t}$ gives:

$$\frac{\partial\mathcal{L}(w^S_{i,t}, \nu_{i,t}, \delta^S_{i,t})}{\partial w^S_{i,t}} = \mathbb{E}_{i,t}[r^S_{t+1} - r_f] - (\gamma + \lambda(F^R_{i,t}))\text{Var}_{i,t}[r^S_{t+1}]w^S_{i,t} + \nu_{i,t} + \delta^S_{i,t} = 0, \tag{A.7}$$

$$\begin{aligned} \frac{\partial\mathcal{L}(\mathbf{w}^B_{i,t}, \nu_{i,t}, \boldsymbol{\delta}^B_{i,t})}{\partial w_{i,t}} \; = \; & \mathbb{E}_{i,t}[\mathbf{r}^B_{t+1} - r_f\mathbf{1}] - (\gamma + \lambda(F^R_{i,t}))\text{Var}_{i,t}[\mathbf{r}^B_{t+1}]\mathbf{w}^B_{i,t} - \gamma\mathbf{a}_{i,t} \circ \text{Cov}_{i,t}[\mathbf{r}^L_{t+1}, \mathbf{r}^B_{t+1}]\frac{1}{F^E_{i,t}} \\ - \; & \lambda(F^R_{i,t})(\mathbf{a}_{i,t} \circ \boldsymbol{\xi}_L \circ \text{Cov}_{i,t}[\mathbf{r}^L_{t+1}, , \mathbf{r}^B_{t+1}])\frac{1}{F^R_{i,t}} + \nu_{i,t} + \boldsymbol{\delta}^{B\prime}_{i,t}\mathbf{1} = 0, \end{aligned} \tag{A.8}$$

$$\frac{\partial \mathcal{L}(w_{i,t}, \nu_{i,t}, \boldsymbol{\delta}_{i,t})}{\partial \nu_{i,t}} = w_{i,t}'\mathbf{1} - 1 = 0. \tag{A.9}$$

This results in the optimal weights:

$$w_{i,t}^{S*} = \underbrace{\frac{\mathbb{E}_{i,t}[r_{t+1}^{S} - r_f] + \nu_{i,t} + \delta_{i,t}^{S}}{(\gamma + \lambda(F_{i,t}^{R}))\mathrm{Var}_{i,t}[r_{t+1}^{S}]}}_{\text{speculative portfolio}} \tag{A.10}$$

$$\begin{aligned}
\mathbf{w}_{i,t}^{B*} &= \underbrace{\frac{\mathbb{E}_{i,t}[\mathbf{r}_{t+1}^{B} - r_f\mathbf{1}] + \nu_{i,t}\mathbf{1} + \boldsymbol{\delta}_{i,t}^{B}}{(\gamma + \lambda(F_{i,t}^{R}))\mathrm{Var}_{i,t}[\mathbf{r}_{t+1}^{B}]}}_{\text{speculative portfolio}} + \underbrace{\frac{\gamma}{\gamma + \lambda(F_{i,t}^{R})}\frac{1}{F_{i,t}^{E}}\mathbf{a}_{i,t} \circ \frac{\mathrm{Cov}_{i,t}[\mathbf{r}_{t+1}^{B}, \mathbf{r}_{t+1}^{L}]}{\mathrm{Var}_{i,t}[\mathbf{r}_{t+1}^{B}]}}_{\text{economic hedging portfolio}} \\
&+ \underbrace{\frac{\lambda(F_{i,t}^{R})}{\gamma + \lambda(F_{i,t}^{R})}\frac{1}{F_{i,t}^{R}}(\mathbf{a}_{i,t} \circ \boldsymbol{\xi}_L \circ \frac{\mathrm{Cov}_{i,t}[\mathbf{r}_{t+1}^{B}, \mathbf{r}_{t+1}^{L}]}{\mathrm{Var}_{i,t}[\mathbf{r}_{t+1}^{B}]})}_{\text{regulatory hedging portfolio}}.
\end{aligned} \tag{A.11}$$

with $\nu_{i,t}$ (if the constraint binds):

$$\begin{aligned}
\nu_{i,t} &= 1 - \frac{\mathbf{1}'\left(\frac{\mathbb{E}_{i,t}[\mathbf{r}_{t+1} - r_f\mathbf{1}] + \boldsymbol{\delta}_{i,t}}{(\gamma+\lambda(F_{i,t}^{R}))\mathrm{Var}_{i,t}[\mathbf{r}_{t+1}]} + (\frac{\gamma}{\gamma+\lambda(F_{i,t}^{R})}\frac{1}{F_{i,t}^{E}}\mathbf{a}_{i,t} \circ \frac{\mathrm{Cov}_{i,t}[\mathbf{r}_{t+1}^{L}, \mathbf{r}_{t+1}^{B}]}{\mathrm{Var}_{i,t}[\mathbf{r}_{t+1}^{B}]})\right)}{\mathbf{1}'(\frac{\mathbf{1}}{(\gamma+\lambda(F_{i,t}^{R}))\mathrm{Var}_{i,t}[\mathbf{r}_{t+1}]})} \\
&- \frac{\mathbf{1}'(\frac{\lambda(F_{i,t}^{R})}{\gamma+\lambda(F_{i,t}^{R})}\frac{1}{F_{i,t}^{R}}(\boldsymbol{\xi}_L \circ \mathbf{a}_{i,t} \circ \frac{\mathrm{Cov}_{i,t}[\mathbf{r}_{t+1}^{L}, \mathbf{r}_{t+1}^{B}]}{\mathrm{Var}_{i,t}[\mathbf{r}_{t+1}^{B}]}))}{\mathbf{1}'(\frac{\mathbf{1}}{(\gamma+\lambda(F_{i,t}^{R}))\mathrm{Var}_{i,t}[\mathbf{r}_{t+1}]})}.
\end{aligned} \tag{A.12}$$

Prior to the UFR, the regulatory funding ratio exactly equaled the economic funding ratio, that is, $F_{i,t}^{E} = F_{i,t}^{R}$, and the optimal weights were a simpler version of (A.11):

$$\mathbf{w}_{i,t}^{B*} = \underbrace{\frac{\mathbb{E}_{i,t}[\mathbf{r}_{t+1}^{B} - r_f\mathbf{1}] + \nu_{i,t}\mathbf{1} + \boldsymbol{\delta}_{i,t}^{B}}{(\gamma + \lambda(F_{i,t}^{E}))\mathrm{Var}_{i,t}[\mathbf{r}_{t+1}^{B}]}}_{\text{speculative portfolio}} + \underbrace{\frac{1}{F_{i,t}^{E}}\mathbf{a}_{i,t} \circ \frac{\mathrm{Cov}_{i,t}[\mathbf{r}_{t+1}^{B}, \mathbf{r}_{t+1}^{L}]}{\mathrm{Var}_{i,t}[\mathbf{r}_{t+1}^{B}]})}_{\text{hedging portfolio}}. \tag{A.13}$$

Appendix D Testable model implications

In this appendix, I derive the model predictions stated in Section III.

Prediction 1 - *P&Is with long liability durations reduce their very long-term maturity holdings and increase those with maturities close to 20 years more compared to P&Is with short liability durations.*

We have that:

$$\lim_{h \to 60} \xi_L(h) \to 0,$$

and hence P&Is with large projected cash flows $a_{i,t}(h)$ in the distant future decrease long-term bond holdings to a larger extent than those with little distant cash flows, because of a stronger reduction in interest rate sensitivities of the liabilities for the former group. Formally, we have that:

$$\lim_{h \to 60, a_{i,t}(60) \to 1} c_{i,t}(h) = -\frac{\lambda(F^R_{i,t})}{\gamma + \lambda(F^R_{i,t})} \frac{1}{F^E_{i,t}} < \lim_{h \to 60, a_{i,t}(60) \to 0} c_{i,t}(h) = 0.$$

Empirically, the distribution of cash flow payments is measured by the liability duration. Hence, my model predicts that P&Is with long liability durations decrease long-term bond holdings more than the ones with short liability durations.

At the same time,

$$\lim_{h \to 20} \xi_L(h) \to 8.41,$$

and hence the demand for bonds with maturities close to 20 years increases more for P&Is with long liability durations specifically because of a larger increase in sensitivity to the 20 year interest rate for those P&Is. Formally, we have that:

$$\lim_{h \to 20, a_{i,t}(20) \to 1} c_{i,t}(h) = \frac{\lambda(F^R_{i,t})}{\gamma + \lambda(F^R_{i,t})} \left(\frac{1}{F^R_{i,t}} \xi_L(h) - \frac{1}{F^E_{i,t}} \right) > \lim_{h \to 20, a_{i,t}(20) \to 0} c_{i,t}(h) = 0.$$

Prediction 2 - *P&Is with long liability durations increase risky asset holdings more compared to P&Is with short liability durations.*

Because of a larger capital relief for P&Is with long liability durations as opposed to those with short liability durations, the weight that is assigned to the regulatory hedging demand, $\lambda(F_{i,t}^R)$, decreases more rapidly for the former group. Formally, the change in the regulatory interest rates is ($UFR = 4.2$ percent):

$$\lim_{h\to 0} \quad \Big(\xi_L(h)y_t^{(h)} + \big(1-\xi_L(h)\big)UFR\Big) - y_t^{(h)} = 0,$$
$$\lim_{h\to 60} \quad \Big(\xi_L(h)y_t^{(h)} + \big(1-\xi_L(h)\big)UFR\Big) - y_t^{(h)} = UFR - y_t^{(h)} > 0.$$

Hence, the P&Is cash flows in the more distant future have a stronger capital relief which, in turn, leads to a higher allocation of risky assets. Formally, if $a_{i,t}(h)$ is large for $h > 20$, then $F_{i,t}^R > F_{i,t}^E$; but if $a_{i,t}(h)$ is small for $h > 20$, then $F_{i,t}^R \approx F_{i,t}^E$. Therefore, following Equation (13), the change in risky asset holdings is:

$$\lim_{h\to 60, a_{i,t}(h)\to 1} c_{i,t}^S = \frac{\mathbb{E}_{i,t}[r_{t+1}^S - r_f] + \nu_{i,t} + \delta_{i,t}^S}{\text{Var}_{i,t}[r_{t+1}^S]}\Big(\frac{1}{\gamma + \lambda(F_{i,t}^R)} - \frac{1}{\gamma + \lambda(F_{i,t}^E)}\Big) > \lim_{h\to 60, a_{i,t}(h)\to 0} c_{i,t}^S = 0.$$

Prediction 3 - *P&Is close to their solvency constraint reduce their very long-term maturity holdings and increase those with maturities close to 20 years more compared to unconstrained P&Is.*

Constrained P&Is put a larger weight on the regulatory hedge demand relative to the economic hedging demand compared to unconstrained ones, and only the regulatory hedging demand is affected by the UFR. Formally, unconstrained investors have a change in demand for bonds that converges to zero at all maturities:

$$\lim_{\lambda(F^R_{i,t})\to 0} \mathbf{c}_{i,t} = 0.$$

Constrained investors have for their long-term holdings the following:

$$\lim_{h\to 60,\lambda(F^R_{i,t})\to\infty} c_{i,t}(h) = -a_{i,t}(h)\frac{1}{F^E_{i,t}} < 0.$$

At the same time, the assets with maturities close to 20 years have ($\lim_{h\to 20} \xi_L(h) \to 8.41$):

$$\lim_{h\to 20,\lambda(F^R_{i,t})\to\infty} c_{i,t}(h) \quad = \quad a_{i,t}(h)\left(\frac{1}{F^R_{i,t}}\xi_L(h) - \frac{1}{F^E_{i,t}}\right) > 0.$$

At the limit, unconstrained investors do not decrease long-term bond holdings nor increase those with maturities close to 20 years, but constrained P&Is do.

Appendix E Cleaning EMIR data

This appendix describes the cleaning steps conducted on the EMIR database.

1. EMIR contains double reporting. This reporting means that both counterparties of a derivative contract, counterparties A and B, have to report the trade. I assume that the perspective of counterparty A is always the correct one, so potential divergences in trade reports between counterparties A and B are ignored.

2. For the purpose of the analysis in this study, swaps based on Euribor are selected.

3. Exclude swap contracts with missing swap rates or floating rates (approximately 0.8 percent).

4. Exclude float-for-float swap contracts (approximately 0.7 percent).

5. Exclude swap contracts that start in the future (approximately 0.4 percent).

6. Exclude duplicate trades (approximately 0.24 percent).

7. Exclude the payment frequency of the swap contract if missing (approximately 0.01 percent).

8. Exclude swap contracts with negative notionals, notionals smaller than 1,000, and notionals larger than 10 billion (approximately 0.01 percent).

9. Exclude swap contracts for which the maturity date is missing or is prior to the reporting date (less than 0.005 percent).

10. Exclude swap contracts for which it is unclear if it is a receiver or payer swap (less than 0.005 percent).

11. Exclude inflation swap contracts (less than 0.005 percent).

12. Exclude swap contracts for which the effective date is missing (less than 0.005 percent).

13. Swap rates should be reported as percentages, so swap rates with an absolute value larger than 10 are divided by 100.

After conducting the cleaning steps above, I have a large database containing the swap contracts of all Dutch counterparties. I then select the insurance companies and pension funds based on their LEI codes.

Institutions have to indicate whether they entered a receiver or payer swap by means of a variable that indicates if they receive the fixed rate or the floating rate. However, some institutions consistently report the opposite of the contract they actually entered. I can detect these mistakes, because institutions also report the market value of the derivative from their perspective. Hence, by computing the price of the swap contract based on the available data in the EMIR database and by comparing that with the reported market values, I can detect these errors. To do so, I compute the price of each swap contract in the following way:

$$V(t, r^{SW}, T_M) = wN\big(P_{r^{SW}}(t, T_M) - P_{FR}(t, T_M)\big), \tag{A.14}$$

where r^{SW} equals the swap rate; w indicates a receiver or payer swap: $w = 1(-1)$ receiver (payer) swap; $P_{r^{SW}}(t, T)$ is the price of the fixed-coupon bond at time t with maturity T_M; $P_{FR}(t, T)$ is the price of a floating rate bond at time t with maturity T; and N is the notional value.

The value of the floating rate bond at time t is calculated as:

$$\begin{cases} P_{FR}(t, T) = 1 & \text{for } t = T_i, T_{i+1} \\ P_{FR}(t, T) = (1 + \Delta^{FR} r_{1/\Delta^{FR}}(T_i))DF(t, T_{i+1}) & \text{for } T_i < t < T_{i+1} \end{cases} \tag{A.15}$$

where T_i is the payment date of the floating leg; T is the maturity date; Δ^{FR} is the payment frequency of the floating rate; $r_{1/\Delta^{FR}}(T_i)$ is the corresponding floating rate at time T_i; and $DF(t, T_{i+1})$ is the discount rate at time t with maturity T_{i+1}. The discount rate is based on the euro OIS zero curve from Bloomberg.

The value of the fixed-coupon bond at time t is calculated similarly:

$$P_{r^{SW}}(t,T) = (\Delta^{FI} r^{SW} \sum_{j=1}^{M} DF(t,T_j) + DF(t,T_M)), \tag{A.16}$$

where T_j indicates the payment date of the fixed leg and Δ^{FI} the payment frequency of the fixed leg.

If the market price that is calculated in Equation (A.14) differs from the reported market value by the institutions themselves in more than 85 percent of the total trades reported in one day, I assume that the reported market values by the institution are correct, and flip receiver (payer) swaps into payer (receiver) swaps.

Appendix F Model implied term structure of interest rates

This appendix solves the equilibrium model outlined in Section VI and provides details on the calibration of the model.

First, the two set of investors in the market have to clear, and thus the market clearing condition implies:

$$\boldsymbol{\alpha}_t^{B*} B_t + \sum_{i=1}^{N} \mathbf{w}_{i,t}^{B*} A_{i,t} = \mathbf{Q}_t, \tag{A.17}$$

where B_t denotes the total wealth of the myopic investors and $\mathbf{Q}_t$ denotes the vector of total supply, whereby $Q_t(h)$ indicates total supply for maturity h.

Plugging in the optimal solution of the myopic investor in Equation (24), solving for $\mathbf{y}_t$, and using Equation (3) results in:

$$\mathbf{y}_t - r_f = \frac{(\mathbf{h}-\mathbf{1})\mathbb{E}_t[\mathbf{y}_{t+1}^B - r_f]}{\mathbf{h}} + \frac{\mathbf{Q}_t - \sum_{i=1}^{N} \mathbf{w}_{i,t}^{B*} A_{i,t}}{B_t} \frac{\gamma \text{Var}_t[\mathbf{y}_{t+1}](\mathbf{h}-\mathbf{1})(\mathbf{h}-\mathbf{1})'}{\mathbf{h}}. \tag{A.18}$$

For the changes in yields that result from the implementation of the UFR we get:

$$\mathbf{y}_t^+ - \mathbf{y}_t = \underbrace{\frac{(\mathbf{h}-\mathbf{1})(\mathbb{E}_t^+[\mathbf{y}_{t+1}^B] - \mathbb{E}_t[\mathbf{y}_{t+1}^B])}{\mathbf{h}}}_{\text{change expectations}} + \underbrace{\frac{1}{B_t} \frac{\gamma \text{Var}_t[\mathbf{y}_{t+1}](\mathbf{h}-\mathbf{1})(\mathbf{h}-\mathbf{1})'}{\mathbf{h}} \sum_{i=1}^{N} \mathbf{c}_{i,t} A_{i,t}}_{\text{change risk-bearing capacity}} \tag{A.19}$$

For the calibration of the model implied term structure of interest rates, I assume that expectations about yields did not change at implementation of the UFR, and hence, yields only change because of a change in risk-bearing capacity. Further, I estimate the covariance matrix using a VAR(1) model that uses the 1, 3, 5, 10, 15, 20 and 30-year Dutch zero-coupon bond yields over the period 1998 to June 30, 2012, when the UFR was implemented. I also assume the off-diagonals of the VAR(1) are zero, because the off-diagonal elements have a negligible effect on the conditional variances. Therefore, the VAR(1) looks as follows:

$$\begin{bmatrix} y_{t+1}^{(1)} \\ y_{t+1}^{(3)} \\ \vdots \\ y_{t+1}^{(30)} \end{bmatrix} = \begin{bmatrix} \alpha^{(1)} \\ \alpha^{(3)} \\ \vdots \\ \alpha^{(30)} \end{bmatrix} + \begin{bmatrix} \rho^{(1)} & 0 & \dots & 0 \\ 0 & \rho^{(3)} & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & \rho^{(30)} \end{bmatrix} \begin{bmatrix} y_t^{(1)} \\ y_t^{(3)} \\ \vdots \\ y_t^{(30)} \end{bmatrix} + \begin{bmatrix} \epsilon_{t+1}^{(1)} \\ \epsilon_{t+1}^{(3)} \\ \vdots \\ \epsilon_{t+1}^{(30)} \end{bmatrix}. \tag{A.20}$$

The conditional covariance matrix $\text{Var}_t[\mathbf{y}_{t+1}]$ is then determined by the covariance matrix of the error terms, multiplied by 252 to convert daily covariances to yearly ones.