Long-term investors and the yield curve*

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Abstract

I provide direct evidence that long-term investors, such as pension funds and insurance companies (P&Is), affect yields by using detailed holdings data combined with price data. In particular, I exploit a change in the regulatory discount curve at which liabilities are evaluated that made the long-end of the discount curve less dependent on market interest rates. Following the regulatory change, P&Is decreased long-term bond holdings by 42 percent on average, whereby the decline is stronger for constrained than unconstrained P&Is. Using an instrumental variable approach, I show that the aggregate decline in demand resulted in an increase of long-term bond yields by 24 basis points on average. My findings are supported by a mean-variance optimization problem in an asset liability context with regulatory constraints.

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

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I. Introduction

Over recent years academics have uncovered suggestive evidence that long-term investors, such as pension funds and insurance companies, affect yields. For instance, Domanski et al. (2017) argue that 'hunt-for-duration' behavior by German insurance companies might have amplified the decline in euro area bond yields. If liabilities are linked to market interest rates, a reduction in interest rates increases the duration gap between assets and liabilities and solvency positions decrease. To reduce their exposure to this risk, long-term investors have an incentive to buy long-term bonds and thereby reducing yields at the long-end of the curve.[1] Additionally, Greenwood and Vayanos (2010) and Greenwood and Vissing-Jorgensen (2018) provide suggestive evidence for regulatory effects on yields. They 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. All these findings are consistent with the preferred habitat view: clientele demand creates price pressure in bond markets.

Because of data limitations, the literature so far uses price data or aggregate holdings data alone to study the implications of the preferred habitat theory. As a result, there are two questions largely left unanswered. First, event studies based on price data alone do not reveal the *magnitude* of the change in demand that is causing the price effect. In other words, how large do changes in holdings have to be in order to have a significant effect on yields? Second, and more importantly, price data or aggregate holdings data alone do not reveal the *motives* of long-term investors to change their bond holdings. For instance, why do investors react to regulatory changes in the first place? Which assets do they buy or sell in return? Do investors close to their solvency constraint react differently to regulatory changes compared to non-constrained ones?

I aim to answer these questions by providing direct evidence how long-term investors react

[1] Similarly, Klinger and Sundaresan (2019) explain the negative 30-year US swap spreads as a result of underfunded pension plans optimally using swaps for duration hedging rather than long-term bonds.

to regulatory changes and how this behavior subsequently affects yields. My study combines holdings data with price data for institutional investors domiciled in the Netherlands. In particular, I exploit a positive shock to the regulatory discount curve at which insurers and pension funds (henceforth: P&Is) have to value their liabilities that was introduced in June 2012. The introduced regulatory discount curve made the long-end of the discount curve less dependent on market interest rates. The discount curve uses market interest rates for maturities up to 20 years, whereas interest rates for maturities exceeding 20 years are set equal to a weighted average between market interest rates and a fixed rate, the Ultimate Forward Rate (UFR). The UFR is substantially higher than market interest rates and as a result, the new regulatory discount curve reduces the value of the liabilities and its sensitivity towards changes in market interest rates.

Why does a change in the regulatory discount curve affect demand for long-term bonds? The demand for long-term bonds arises mainly in two parts: economic and regulatory hedging incentives. The long-term nature of P&Is' liabilities creates a natural preference for long-term bonds from a liability hedge 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 are operating. For instance, the regulatory discount curve is important in solvency assessments, as its used to estimate the solvency position and hence the financial position of P&Is. As a result, incentives to hedge the regulatory discount curve may increase if the regulatory discount curve diverges from the economic discount curve. The introduction of the UFR thus decreased regulatory hedging demand whereas economic hedging demand was unaffected. The extent to which regulatory hedging demand decreases, as I show, depends on the liability structure and solvency positions of P&Is.

I report the following key results. First, I find that P&Is that are more exposed to the regulatory change, i.e. the ones with long liability durations, decrease long-term bond holdings to a larger extent than less exposed ones. The decrease in long-term bond holdings is economically significant: The total decline in long-term bond holdings ($T \geq 30$) due to the regulatory change equals 15.30 billion, which is equivalent to a relative decrease in demand of 42 percent. Besides, to give additional support for the economic effects, P&Is in my sample invest 20 percent of their bond portfolio in Dutch government bonds, which implies a total decline in Dutch long-term bond holdings of 3.06 billion and corresponds to 22 percent of its total amount outstanding. Second, I find that P&Is close to their solvency constraint decrease long-term holdings to a larger extent than non-constrained ones. Third, P&Is increase their allocation to equities following the regulatory change, with a stronger effect for more constrained P&Is. These findings are consistent with a mean-variance optimization problem in an asset liability context with regulatory constraints.

In the second part of the paper I show the asset pricing implications of P&I demand for long-term bonds. I find that yields go down following a fall in the aggregate solvency position of P&Is. To cleanly identify the effects of demand on yields, I apply an instrumental variable approach that uses the weights assigned to the UFR for different maturity buckets as instrument for changes in demand. I show that the change in the regulatory discount curve results in an increase of Dutch long-term bond yields by 24 basis points on average, with larger magnitudes for longer maturity bonds. My estimates are larger than the estimates found by typical event studies because P&Is did not sell everything at once, but spread out the decrease in long-term bond holdings over multiple periods.

In the final part of the paper, I connect the changes in yields to responses in the demand curves of the different investor types by using the framework of Koijen and Yogo (2019). The estimates show substantial heterogeneity in demand curves across investor types, with P&Is having strong upward sloping demand curves in prices, whereas demand curves are strongly downward sloping for banks and the foreign sector. Moreover, the steepness of the upward sloping demand curves depends, as I show, on the liability duration and solvency positions of P&Is. These findings add to further understand the drivers behind the estimated price effect. Additionally, they are important for the recent intermediary asset pricing literature which directly models intermediaries and how they matter for asset prices, e.g. He and Krishnamurthy (2013). Typically, these models use only one class of intermediaries. My results highlight the importance of incorporating heterogeneity across investor types in order to understand the effects of intermediaries on asset prices, adding to findings of Greenwood et al. (2018), Timmer (2018), and Koijen and Yogo (2019).

My findings also have important policy implications. In recent years, government bond yields have not always reacted in a predictable way to macroeconomic or monetary policy announcements. For instance, long-term yields in the US remained low even as the FED initiated a series of interest rate increases away from zero starting in 2015. My findings show that regulation plays an important role in understanding these patterns. The demand for bonds by long-term investors increases when interest rates decline, reinforcing the decline in long-term yields. My results show that this reinforcing effect decreases if the valuation of assets and liabilities becomes less dependent on market interest rates. Policy makers should take the regulatory framework of long-term investors into account when analyzing the impact of conventional and unconventional monetary policies.

Related Literature

This paper contributes to the preferred-habitat theory proposed by Culbertson (1957) and Modigliani and Sutch (1966), who argue that there are investor clienteles with preferences for specific maturities, and the interest rate for a given maturity is influenced by the demand of the corresponding clientele and the supply of bonds with that maturity. Vayanos and Vila (2009) and Greenwood and Vayanos (2014) study supply effects on yields. Supply shocks positively affect yields, because supply shocks change the amount of bonds arbitrageurs are holdings and thus the duration risk they carry. Similarly, Guibaud et al. (2013) model a clientele-based yield curve. They show that an increase in the relative importance of the clientele with the longer investment horizon, i.e. 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 showing direct empirical evidence in favor of the preferred habitat theory by using data on holdings and yields simultaneously.

My paper also links to the recent demand based asset pricing literature. For instance, Koijen and Yogo (2019) propose an asset pricing model with flexible heterogeneity in asset demand across investors. Koijen et al. (2017) and Koijen et al. (2020) apply this model to study the effects of quantitative easing in the euro area. I contribute to this work by relating institutional investor specific characteristics to their demand curves. For instance, I show that the steepness of the upward sloping demand curves of P&Is depends on their liability durations and solvency positions.

This paper also links to Sen (2019), who studies interest rate risk hedging activities by US life insurers after a shift in regulation. The regulatory change leads to distorted hedging incentives due to different treatments of interest rate risk for products with similar economic exposures. Insurers underwriting products that are regulatory sensitive to interest rates do increase hedging activities, and vice versa. I contribute to this paper in two ways: (1) studying spillovers to other asset classes following a shift in hedging incentives and (2) linking changes in hedging incentives to changes in long-term yields.

The remainder of the paper is organized as follows. I start with describing the introduction of the regulatory discount curve based on the UFR in Section II. Section III provides a simple model to derive testable implications of the effect of the change in the regulatory discount curve on long-term bond holdings and yields. 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 by using an instrumental variable approach. Section VII concludes.

II. Institutional setting - Ultimate Forward Rate (UFR)

The regulatory discount curve is important in solvency assessments, as its used to estimate the funding position and hence the financial position of P&Is. As such, it shows whether

P&Is are expected to meet nominal obligations. Important decisions are made based on the funding positions, such as the amount of dividends paid to the shareholders or the ability to index pension rights. In the Netherlands, the Dutch Central Bank (DNB) constructs and publishes the regulatory discount curve on a monthly basis.

A. Regulatory discount curve without UFR

Prior to the end of June 2012, the regulatory discount curve at which P&Is had to value their liabilities was entirely based on the euro swap curve for all maturities. Market interest rates were used until a maturity of 50 years, and interest rates with maturities beyond 50 years equaled the last observed forward rate. Because the regulatory discount curve was based on market interest rates only, the regulatory discount curve approximately equaled the economic discount curve. Formally, the regulatory discount curve was constructed as follows:[2]

1. European semi-annual swap rates from Bloomberg for the time to maturities 1 to 10, 12, 15, 25, 30, 40, and 50 years.[3]

2. Zero-coupon interest rates are derived from the swap rates by using bootstrapping (Veronesi 2010).

3. Interest rates for which swap rates are non-observable are estimated by assuming constant forward rates, thereby iterating the following relationship:

$$(1 + y^{(h)})^h = (1 + y^{(h-1)})^{h-1}(1 + f_{h-1}^h) \tag{1}$$

   where $y^{(h-1)}$ equals the interest rate for time to maturity $h-1$ and f_{h-1}^h the forward rate for time-to-maturity $h-1$ to h. For instance, the forward rate from 24 to 25 years

[2] See https://www.toezicht.dnb.nl/binaries/50-212329.pdf.

[3] Bloomberg also offers swap rates for all maturities from 1 to 30 years, and for 35 and 45 year time to maturities. However, the regulator refrained from using some of these interest rates because of less liquid markets for these maturities.

(f_{24}^{25}) is used to derive the zero-coupon interest rates with maturities 26-29 years.

B. Regulatory discount curve with UFR

DNB announced a change in the regulatory discount curve to anticipate on the new regulatory framework of Solvency II for insurance companies on July 2, 2012. The introduced regulatory discount curve is similar to the regulatory discount curve applicable to all European insurers when Solvency II was introduced in 2016. DNB announced a similar regulatory discount curve for pension funds on September 24, 2012.

The new regulatory discount curve uses an extrapolation method based on the UFR, where the UFR is the convergence of long interest rates to a stable level. In essence, the regulatory discount curve with UFR uses market interest rates up to a maturity of 20 years, and interest rates with maturities longer than 20 years are determined by combining market interest rates and a fixed rate, the UFR. The main argument that was used to justify the implementation of the UFR is that the market for long durations (>20 years) is fairly illiquid and only few securities with such long durations exists. As a result, the implied market interest rates were regarded unreliable: a discount curve purely based on market data is highly sensitive to supply and demand shocks, and therefore also the solvency positions of P&Is. A regulatory discount curve based on the UFR solves this issue by making long-term interest rates less dependent on market interest rates.

Formally, the discount curve with UFR is constructed as follows:

1. For maturities 1 to 20, zero-coupon interest rates are still derived as before (steps 1-3 in Subsection A).

2. For pension funds, forward rates exceeding maturities of 20 years are a weighted average between the market forward rate and the UFR. The weights are constant over time.

As of a maturity of 60 years, forward rates equal the UFR:

$$f_{h-1}^{h,*}\begin{cases} f_{h-1}^{h} & 1 \leq h \leq 20 \\ (1-w_h)\times f_{h-1}^{h} + w_h \times \text{UFR} & 21 \leq h \leq 60 \\ \text{UFR} & h \geq 60 \end{cases} . \tag{2}$$

For insurance companies, the regulatory discount curve is slightly different and uses the forward rate $f_{h-1}^{h} = f_{19}^{20}$ for all maturities $21 \leq h \leq 60$.

3. The weights are equal to

$$w_h = \frac{f_{h-1}^{h,SW} - f_{19}^{20}}{f_{60}^{61,SW} - f_{19}^{20}} \qquad \text{for} \qquad h = 21, ..., 60, \tag{3}$$

where $f_{h-1}^{h,SW}$ are the one year forward rates that follow from the Smith-Wilson method.[4] The Smith-Wilson technique uses the following parameter values: the last liquid point which defines the start of the UFR equals 20 years, the full convergence to the UFR equals 60 years, the UFR level equals 4.2%, and the convergence parameter that defines how quickly the discount curve converges to the UFR equals $\alpha = 0.1$. Details on the parameter values for the Smith-Wilson technique are described in Appendix A. Table 15 shows the corresponding weights, where the weights are fixed and increase in h.

4. Zero-coupon interest rates $y^{(h)}$ are computed as follows:

$$(1+y^{(h)})^h = \prod_{n=1}^{h}(1+f_{n-1}^{n,*}) \qquad \text{for} \qquad h = 1, 2, ...120 \tag{4}$$

The regulatory discount curve with UFR has two important effects. First, it decreases current liability values as liabilities are discounted against higher rates. Second, it decreases

[4]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.

the impact of interest rate changes. Figure 1 shows both effects. The red solid line shows the economic discount curve and the blue solid line the economic discount curve after a parallel shock in interest rates of -1%. The dashed green line and the dotted black line show the same discount curves including the UFR.

[Place Figure 1 about here]

C. Impact of the UFR on the liability value

In order to show the economic effects of the UFR, I compute the liability value using both the economic and the regulatory discount curve. Figure 2 shows the cash flow pattern of a (fictitious) pension fund. The cash flows are the average cash flow patterns across the Dutch pension funds in my sample.[5] The peak of the cash flow distribution is at a maturity of 20 years, reflecting the importance of the UFR as half of the cash flows materialize at maturities beyond 20 years. The cash flows allow me to compute the value of the liabilities both under the economic and regulatory discount curve. Formally, I compute:

$$L_t = \sum_{n=1}^{N} \frac{CF_n}{(1 + y_t^{(n)})^n} \tag{5}$$

where CF_n are the average projected pension payments for maturity n, where $y_t^{(n)} = y_{E,t}^{(n)}$ under the economic discount curve and $y_t^{(n)} = y_{R,t}^{(n)}$ under the regulatory discount curve.

In Table 1, I compute the liability values for the projected pension payments for an average pension fund in my sample using the discount curve with and without UFR on September 30, 2012. Moreover, the table shows the change in the liability value after a parallel decrease in the economic discount curve of 1%. The liability value at implementation of the UFR decreases with 664 million for the average pension fund, or a decrease of 4.23%. This reflects the first effect of the UFR: a direct decrease in the liability values. The average

[5] I explain the cash flow data in more detail in Section IV.

liability value after a negative 1% parallel shift in interest rates equals 19,878 million using the economic discount curve, whereas using the regulatory discount curve this value equals 18,433 million. In other words, the increase in the value of liabilities equals 3,518 million after the negative interest rate shock pre UFR, and only increases with 2,737 million at implementation of the UFR, or a relative decrease of 28.5%. This reflects the second effect of the UFR: a dampening impact of changes in interest rates on liability values, which is much larger in magnitude than the first effect. Obviously, this effect is particularly visible looking at cash flows that materialize after 20 years in isolation. A negative 1% parallel shock in interest rates increases the value of the liabilities with 1,680 million after implementation of the UFR, which is 46.5% less than the increase in the liability value prior to the implementation of the UFR.

[**Place Figure 2 about here**]

[**Place Table 1 about here**]

D. The effect of the UFR on bond yields

The introduction of the UFR had a significant effect on Dutch long-term bond yields, as already documented by Greenwood and Vissing-Jorgensen (2018). Figure 3 shows the 30-20 government bond spread. The spread increased significantly after the announcement of the UFR, and remained at a higher level thereafter. In Section VI, I study the change in yields due to the introduction of the UFR using an instrumental variable approach to cleanly identify the asset pricing effect. Moreover, I connect the changes in yields to responses in the demand curves of the different investor types by using the framework of Koijen and Yogo (2019). This allows me to study the importance of different investor types in creating asset pricing effects.

[**Place Figure 3 about here**]

III. Model

I derive my main testable predictions from a mean-variance optimization framework with liabilities, where P&Is care about both their economic and regulatory solvency constraints. Prior to the UFR, economic and regulatory hedging demand were identical, whereas after implementation of the UFR regulatory hedging demand deviated from economic hedging demand. The extent to which economic and regulatory hedging demand deviate depends on the liability structure and solvency positions of P&Is. This results in heterogeneity in the effect of the regulatory change on long-term bond holdings across P&Is.

To derive testable asset pricing implications of P&I demand for long-term bonds, I close the section by solving a simple equilibrium framework where arbitrageurs, or myopic investors, determine yields in equilibrium.

A. The financial market

The financial market consists of an equity index and a set of bonds. The equity index is denoted by S_t and its corresponding return by r^S_{t+1}. The set of bonds is denoted by B_t, where a particular bond is characterized by its maturity h and corresponding yield $y^{(h)}_t$.

The return on each bond is defined as:

$$r^{(h-1)}_{t+1} = \ln(\frac{P^{(h-1)}_{t+1}}{P^{(h)}_t}) = y^{(h)}_t - (h-1)[y^{(h-1)}_{t+1} - y^{(h)}_t]. \tag{6}$$

The vector of bond returns is denoted by r^B_{t+1}, the return expectations by $\mathbb{E}_t[r^B_{t+1}]$, and the variance-covariance matrix by $\text{Var}_t[r^B_{t+1}]$. I assume that the bond returns are imperfectly correlated, whereas the equity index and the set of bonds are uncorrelated. Furthermore, I assume throughout that the yield curve can be determined using the set of bonds.

B. Long-term investors

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

$$A_{t+1} = \Big(R_f + w_t^S(r_{t+1}^S - r_f) + w_t^{B'}(r_{t+1}^B - r_f)\Big)A_t, \tag{7}$$

where R_f equals the gross risk-free interest rate, w_t^S the portfolio weight to stocks and w_t^B the vector of portfolio weights to the bonds.

For the liabilities, I assume P&Is have to pay out a fixed set of cash flows CF_t, where each cash flow is characterized by its maturity h. I also assume that P&Is have a large enough number of participants such that idiosyncratic longevity risk is fully diversified. Large projected cash flows for long maturities h implies that liabilities have to be paid out in the more distant future. Finance theory implies that risk-free market interest rates are the applicable discount for guaranteed benefits to exclude arbitrage. The economic value of the liabilities at time t therefore equals:

$$L_t^E = \sum_h CF_t^{(h)} \exp(-hy_t^{(h)}). \tag{8}$$

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

$$\begin{aligned} L_{t+1}^E &= \sum_h CF_t^{(h)} \exp(-hy_t^{(h)})\Big(1 + y_t^{(h)} - (h-1)(y_{t+1}^{(h-1)} - y_t^{(h)})\Big) \\ &= a_t' R_{t+1}^B L_t^E, \end{aligned} \tag{9}$$

where

$$a_t^{(h)} = \frac{CF_t^{(h)} \exp(-hy_t^{(h)})}{L_t^E}. \tag{10}$$

Notice that the discounted cash flows are P&I specific, so that $a_t^{(h)}$ is high for long maturities

h if the corresponding cash flow $CF_t^{(h)}$ is large relative to L_t^E.

The regulatory value of the liabilities is similar to its economic counterpart, except that for long maturities the regulatory discount curve is less sensitive to market interest rates. The sensitivity of the regulatory discount curve to market interest rates is defined by ξ_L, where ξ_L has the same length as the set of bonds and $0 \leq \xi_L^{(h)} \leq 1$ for all h. This means that the economic and regulatory value of the liabilities are identical if $\xi_L^{(h)} = 1$ for all h, as was the case prior to implementation of the UFR. If on the other hand $\xi_L^{(h)} = 0$ for all h, the regulatory value of the liabilities is insensitive to changes in interest rates. An example is a regulatory discount curve that uses a fixed rate for all maturities. In case of the specific event I look at here, the introduction of the UFR, we have that $\xi_L^{(h)} = 1$ for $h \leq 20$ and $\xi_L^{(h)} < 1$ for $h > 20$. The regulatory value of the liabilities thus evolves as:

$$L_{t+1}^R = (\xi_L \circ a_t)' R_{t+1}^B L_t^R, \tag{11}$$

where $(\circ)$ is the Hadamard product.

I furthermore assume P&Is have mean-variance preferences over the assets minus liabilities, or the surplus, 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. Important decisions are made based on funding positions of P&Is, such as the amount of dividends paid to shareholders or the ability to index pension rights. The optimization problem of P&Is equals:

$$\begin{aligned} \max_{w_t} \quad & \mathbb{E}[u(\frac{A_{t+1}}{A_t} - \frac{L_{t+1}}{A_t})] \\ = \quad & \arg\max_{w_t} \mathbb{E}[\frac{A_{t+1}}{A_t}] - \frac{\gamma}{2}\text{Var}[\frac{A_{t+1}}{A_t} - \frac{L_{t+1}^E}{A_t}] - \frac{\lambda(F_t^R)}{2}\text{Var}[\frac{A_{t+1}}{A_t} - \frac{L_{t+1}^R}{A_t}], \end{aligned} \tag{12}$$

subject to

$$w_t' \iota = w_t^S + w_t^{B} \iota \leq 1, \tag{13}$$

$$w_t^S, w_{h,t}^B \geq 0 \qquad \forall h, \tag{14}$$

where γ equals the risk-aversion parameter, $F_t^R = \frac{A_t}{L_t^R}$, and $\lambda(F_t^R)$ defines the importance of the regulatory funding ratio. As in Sen (2019), I assume that the variance of the regulatory funding ratio is proportional to $\lambda(F_t^R)$, where $\lambda'(F_t^R) < 0$, or in other words P&Is care more about the regulatory funding ratios when the regulatory funding ratio is low. I additionally assume that $\lambda(F_t^R)$ is convex: P&Is care more about a decline in the regulatory funding ratio when the regulatory funding ratio is already low than in case its high.

As I show in Appendix B, solving for w_t results in:

$$w_t^{S*} = \underbrace{\frac{\mathbb{E}_t[r_{t+1}^S - r_f] + \nu_t + \delta_t^S}{(\gamma + \lambda(F_t^R))\mathrm{Var}_t[r_{t+1}^S]}}_{\text{speculative portfolio}}, \tag{15}$$

$$w_t^{B*} = \underbrace{\frac{\mathbb{E}_t[r_{t+1}^B - r_f] + \nu_t \iota + \delta_t^B}{(\gamma + \lambda(F_t^R))\mathrm{Var}_t[r_{t+1}^B]}}_{\text{speculative portfolio}} + \underbrace{\frac{\gamma}{\gamma + \lambda(F_t^R)} a_t \frac{1}{F_t^E}}_{\text{economic hedging portfolio}} + \underbrace{\frac{\lambda(F_t^R)}{\gamma + \lambda(F_t^R)} (\xi_L \circ a_t) \frac{1}{F_t^R}}_{\text{regulatory hedging portfolio}}, \tag{16}$$

with

$$\begin{aligned} w_t^{*S}, w_{h,t}^{*B} &\geq 0, \\ \delta_t^S, \delta_{h,t}^B &\geq 0, \\ \delta_t^S w_t^{S*} = 0, \delta_{h,t}^B w_{h,t}^{B*} &= 0 \ \forall h, \end{aligned}$$

where ν_t equals the Lagrange multiplier for the restriction that $w_t'\iota = 1$, and δ_t the Kuhn-Tucker multipliers for the restrictions that the portfolio weights are nonnegative.

The optimal demand for stocks consists of speculative demand only, because the liabilities are valued using the yield curve and yields are assumed to be independent of the stocks. The liability hedge 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 relative weights of the liabilities in the different maturity buckets. Second, the weight assigned to the economic versus regulatory hedging demand depends on the relative magnitudes of $\lambda(F_t^R)$ and γ, which is driven by solvency positions.

These results together lead to three important model implications. Throughout I indicate variables at implementation of the UFR with a plus sign ($^+$).

Implication 1 - bond holdings

Prior to the UFR, the regulatory funding ratio exactly equals the economic funding ratio, i.e. $F_t^E = F_t^R$, and the optimal weights are defined as:

$$w_t^{B*} = \frac{\mathbb{E}_t[r_{t+1}^B - r_f] - \nu_t \iota + \delta_t^B}{(\gamma + \lambda(F_t^E))\text{Var}_t[r_{t+1}^B]} + a_t \frac{1}{F_t^E} \tag{17}$$

Right after implementation of the UFR, the optimal holdings equal:

$$w_t^{B*+} = \frac{\mathbb{E}_t[r_{t+1}^B - r_f] - \nu_t \iota + \delta_t^B}{(\gamma + \lambda(F_t^R))\text{Var}_t[r_{t+1}^B]} + \frac{\gamma}{\gamma + \lambda(F_t^R)} a_t \frac{1}{F_t^E} + \frac{\lambda(F_t^R)}{\gamma + \lambda(F_t^R)} (\xi_L \circ a_t) \frac{1}{F_t^R} \tag{18}$$

Subtracting (17) from (18), we get the change in holdings due to the implementation of the UFR:

$$\begin{aligned} c_t = w_t^{B*+} - w_t^{B*} &= \underbrace{\frac{\mathbb{E}_t[r_{t+1}^B - r_f] - \nu_t \iota + \delta_t^B}{\text{Var}_t[r_{t+1}^B]} \left(\frac{1}{\gamma + \lambda(F_t^R)} - \frac{1}{\gamma + \lambda(F_t^E)} \right)}_{\textbf{change in speculative demand>0}} \\ &+ \underbrace{\frac{\lambda(F_t^R)}{\gamma + \lambda(F_t^R)} \left((\xi_L \circ a_t) \frac{1}{F_t^R} - a_t \frac{1}{F_t^E} \right)}_{\textbf{change in liability hedge demand<<0}} \leq 0 \end{aligned} \tag{19}$$

Because $F_t^E < F_t^R$ we have that speculative demand increases, whereas liability hedge demand decreases. Because the UFR substantially declines the sensitivity towards interest rate changes, but only leads to a small decline in funding ratios[6], the decline in the liability hedge portfolio is substantially stronger than the increase in the speculative portfolio. Moreover, because we have that $\xi_L^{(h)} < 1$ for $h > 20$ and $\xi_L^{(h)}$ converges to zero for very long maturities, P&Is with large projected cash flows in the distant future decrease long-term bond holdings to a larger extend than the ones with projected cash flows in the near future. In other words, my model predicts that P&Is with long liability durations decrease long-term bond holdings more than the ones with short liability durations.

Implication 2 - bond holdings

Constrained P&Is put a larger weight on the regulatory hedging demand relative to the economic hedging demand compared to non-constrained ones, and only regulatory hedging demand is affected by the UFR. Formally, for non-constrained investors we have:

$$\lim_{\lambda(F_t^R)\to 0} w_t^{B*+} - w_t^{B*} = 0. \tag{20}$$

For constrained investors we have ($\xi_L^{(h)} < 1$ and $F_t^E < F_t^R$):

$$\lim_{\lambda(F_t^R)\to \infty} w_t^{B*+} - w_t^{B*} = \left((\xi_L \circ a_t) \frac{1}{F_t^R} - a_t \frac{1}{F_t^E} \right) < 0. \tag{21}$$

In the limit unconstrained investors do not decrease long-term bond holdings, whereas constrained P&Is do.

Implication 3 - stock holdings

My model also predicts a positive change in the stock holdings due to implementation of the

[6]The average increase in the regulatory funding ratio is from 0.99 to 1.03, or exactly the 4% difference in the change in the liability value (see Table 1).

UFR ($\lambda(F_t^R) < \lambda(F_t^E)$):

$$w_t^{S*+} - w_t^{S*} = \underbrace{\frac{\mathbb{E}_t[r_{t+1}^S - r_f] - \nu_t\iota + \delta_t^S}{\text{Var}_t[r_{t+1}^S]}\Big(\frac{1}{\gamma + \lambda(F_t^R)} - \frac{1}{\gamma + \lambda(F_t^E)}\Big)}_{\textbf{change in speculative demand}} > 0 \tag{22}$$

Because the weight that is assigned to the regulatory hedging demand, $\lambda(F_t^R)$, decreases more sharply for P&Is with low funding ratios than for the ones with high funding ratios at implementation of the UFR (convexity), the speculative demand for stocks increases more for P&Is with low funding ratios.

C. Testable predictions holdings

The first prediction of the model is that the decrease in long-term bond holdings is stronger for P&Is with long liability durations at implementation of the UFR:

Prediction 1 - bond holdings P&Is with long liability durations decrease long-term holdings more compared to P&Is with short liability durations.

Second, the model shows that more capital constrained P&Is decrease long-term holdings to a larger extent compared to non-constrained ones because they have a stronger incentive to hedge the regulatory value of the liabilities. This leads to the second prediction:

Prediction 2 - bond holdings P&Is close to their solvency constraint decrease long-term holdings more compared to non-constrained P&Is.

Third, the model predicts that more capital constrained P&Is increase their stock holdings to a larger extent than less constrained ones:

Prediction 3 - stock holdings P&Is close to their solvency constraint increase stock holdings more compared to non-constrained P&Is.

D. Model implied impact on yields

Why would the change in long-term bond holdings have such a significant effect on Dutch long-term yields? The regulatory change introduces a shock to the demand for long-term bonds. However, the supply of long-term bonds was not affected by the regulatory change. This implies that the interest rate risk, or duration risk, carried by other investors in the market increases. In the preferred habitat models of Vayanos and Vila (2009) and Greenwood and Vayanos (2014), these other investors are defined as the arbitrageurs.[7] In order to carry the increased duration risk, arbitrageurs (or myopic investors) require a higher return on the long-term bond. The level, however, depends on the risk-bearing capacity of the myopic investors.

I start with describing the optimization problem of the myopic investor. The wealth of the myopic investor evolves as follows:

$$B_{t+1} = \Big(R_f + \alpha_t'(r_{t+1}^B - r_f)\Big)B_t. \tag{23}$$

The myopic investor has mean-variance preferences over excess returns:

$$\max_{\alpha_t} \mathbb{E}_t[\frac{B_{t+1}}{B_t}] - \frac{\gamma}{2}\text{Var}_t[\frac{B_{t+1}}{B_t}] \quad = \quad R_f + \alpha_t'\mathbb{E}_t[r_{t+1}^B - r_f] - \frac{\gamma}{2}\alpha_t'\text{Var}_t[r_{t+1}^B]\alpha_t, \tag{24}$$

Solving for α_t^*, the optimal solution to the mean-variance investors equals:

$$\alpha_t^* = \frac{\mathbb{E}_t[r_{t+1}^B - r_f]}{\gamma \text{Var}_t[r_{t+1}^B]}, \tag{25}$$

First, the two set of investors in the market have to clear. This implies that the yields are determined endogenously depending on the preferences of the long-term and myopic

[7]Similarly, to explain the bond pricing implications of the prepayment option in MBS in the US, Hanson (2014) assumes arbitrageurs price interest rate risk in the market.

investors. Therefore, the market clearing condition implies:

$$\alpha_t^{(h)} B_t + w_t^{(h)} A_t = Q_t^{(h)} \quad \text{for all } h. \tag{26}$$

Plugging in the optimal solution of the myopic investor (25) for $\alpha_t^{(h)}$, solving for $y_t^{(h)}$ and using (6) results in:

$$y_t^{(h)} - r_f = \frac{(h-1)(\mathbb{E}_t[y_{t+1}^{(h-1)}] - r_f)}{h} + \frac{Q_t^{(h)} - w_t^{(h)} A_t}{B_t} \frac{\gamma(h-1)^2 \text{Var}_t[y_{t+1}^{(h-1)}]}{h} \tag{27}$$

where $Q_t^{(h)} - w_t^{(h)} A_t$ is equal to the wealth of the myopic investor in maturity bucket h, i.e. $B_t^{(h)} = Q_t^{(h)} - w_t^{(h)} A_t$. Moreover, this implies that the excess return equals:

$$\mathbb{E}_t[r_{t+1}^{(h-1)}] - r_f = \frac{Q_t^{(h)} - w_t^{(h)} A_t}{B_t} \gamma(h-1)^2 \text{Var}_t[y_{t+1}^{(h-1)}]. \tag{28}$$

In other words, the excess return decreases in the holdings of long-term investors: the larger the holdings of the long-term investors, the less interest rate risk has to be carried by the myopic investors, which decreases expected returns. The optimal solution of the demand for long-term bonds by P&Is in (16) decreases in the aggregate solvency position of P&Is. My model thus predicts excess bond returns to increase after a fall in the aggregate solvency positions.

Second, the market clearing condition should still hold after implementation of the UFR[8], which implies an excess return that equals:

$$\mathbb{E}_t^+[r_{t+1}^{(h-1)}] - r_f = \frac{Q_t^{(h)} - w_t^{(h)+} A_t}{B_t} \gamma(h-1)^2 \text{Var}_t^+[y_{t+1}^{(h-1)}] \tag{29}$$

Under the assumption that the conditional variance of future yields does not change because of the introduction of the UFR, i.e. $\text{Var}_t[y_{t+1}^{(h-1)}] = \text{Var}_t^+[y_{t+1}^{(h-1)}]$, subtracting (29)

[8] i.e. $\alpha_t^{(h)+} B_t + w_t^{(h)+} A_t = Q_t^{(h)}$

from (28) results in:

$$\begin{aligned}\mathbb{E}_t^+[r_{t+1}^{(h-1)}] - \mathbb{E}_t[r_{t+1}^{(h-1)}] &= \frac{(w_t^{(h)} - w_t^{(h)+})A_t}{B_t}\gamma(h-1)^2\text{Var}_t[y_{t+1}^{(h-1)}] \\ &= \frac{c_t^{(h)}A_t}{B_t}\gamma(h-1)^2\text{Var}_t[y_{t+1}^{(h-1)}] \end{aligned} \tag{30}$$

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

$$y_t^{(h)+} - y_t^{(h)} = \underbrace{\frac{(h-1)(\mathbb{E}_t^+[y_{t+1}^{(h-1)}] - \mathbb{E}_t[y_{t+1}^{(h-1)}])}{h}}_{\text{change expectations}} + \underbrace{\frac{c_t^{(h)}A_t}{B_t}\frac{\gamma(h-1)^2\text{Var}_t[y_{t+1}^{(h-1)}]}{h}}_{\text{change risk-bearing capacity}} \tag{31}$$

This result shows that the price impact of the regulatory change depends on changes in expectations about future yields, $\mathbb{E}_t^+[y_{t+1}^{(h-1)}] - \mathbb{E}_t[y_{t+1}^{(h-1)}]$, the demand shock, $c_t^{(h)}$, the risk-aversion parameter γ, and the wealth of the arbitrageurs, B_t, relative to the wealth of the long-term investors, A_t. Equation (28) and (31) result in the following two additional model implications.

Implication 3 - future excess returns and yields

Future excess returns decrease if the aggregate holdings of P&Is increase:

$$\lim_{w_t^{(h)}A_t \to Q_t^{(h)}} \mathbb{E}_t[r_{t+1}^{(h-1)}] - r_f = 0, \tag{32}$$

and

$$\lim_{w_t^{(h)}A_t \to 0} \mathbb{E}_t[r_{t+1}^{(h-1)}] - r_f = \frac{Q_t^{(h)}}{B_t}\gamma(h-1)^2\text{Var}_t[y_{t+1}^{(h-1)}] > 0. \tag{33}$$

Implication 4 - future excess returns and yields

Under the assumption that expectations about future yields did not change or increased, i.e. $\mathbb{E}_t^+[y_{t+1}^{(h-1)}] - \mathbb{E}_t[y_{t+1}^{(h-1)}] \geq 0$, the regulatory change increases the risk-bearing capacity of myopic investors and hence yields increase:

$$y_t^{(h)+} - y_t^{(h)} \geq \frac{c_t^{(h)} A_t}{B_t} \frac{\gamma(h-1)^2 \text{Var}_t[y_{t+1}^{(h-1)}]}{h} > 0 \quad (34)$$

E. Testable predictions future excess returns and yields

The model predicts that future excess return increase if long-term investors hold a smaller share of long-term bond holdings, which according to my model occurs if the funding ratio is high:

Prediction 3 - future excess returns and yields Yields and future excess bond returns are negatively related to the aggregate funding positions of P&Is.

Second, the UFR leads to a structural decrease in P&Is long-term bond holdings, which, in turn, increase the yields:

Prediction 4 - future excess returns and yields Yields increase due to the implementation of the UFR.

IV. Data

In this section I describe the three data sources that I use for my analysis: the SHS database (Subsection A), the CSDB database (Subsection B), and the supervision database (Subsection C).

A. SHS database

I use Dutch security holdings (SHS) data for four types of institutional investors: banks, insurance companies, investment funds, and pension funds. 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, with the aim 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.[9]

DNB gathers holdings data to setup, among others, the Dutch balance of payments, the international investment position, and the financial accounts, and subsequently reports the holdings data to the ECB for the setup of the aforementioned statistics at an euro area level. The data that I use is therefore also available at the euro area level. I have three main reasons to use the Dutch data instead. First, the European data starts at the end of 2013 only, whereas introductions of the ultimate forward rates (UFR) in several European countries already happened in 2011 and 2012. Moreover, the European data aggregates over all sectors, whereas the Dutch data is at the institutional level. This allows me to make use of the cross-sectional variation in institutions. For instance, measuring effects of the solvency positions on holdings is only possible when there is data availability at the institutional level. Third, looking at the total AUM of pension funds alone in my database, I already cover 53 percent of the assets of pension funds in the euro area, OECD (2019).

The data provide bond and stock holdings at the International Securities Identification Number (ISIN) level. 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. For stocks, start and end holdings are available in number of shares and market values. For bonds, start and end holdings are available in both nominal and market values.

B. CSDB database

The SHS database is linked to the Centralised Securities Database (CSDB). The aim of the CSDB database is to hold accurate information on all individual securities relevant for the statistical purposes of the European System of Central Banks, ECB (2010). From the CSDB database I obtain market relevant information: debt type, maturity dates, coupon

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

rates, coupon frequencies, coupon type (e.g. fixed, floating or zero-coupon), last coupon payment date, yield-to-maturity, and closing price. The data from the CSDB database allows me to assign bonds in maturity buckets and compute bond durations. The procedure to compute bond durations for every bond type is outlined in Appendix C.

C. Supervision database

The supervision database is from mandatory annual and quarterly statements that P&Is report to DNB. P&Is have to report, among others, solvency positions, the value of the assets and liabilities, liability durations, asset allocations, and derivative positions. I describe the solvency requirements for both pension funds and insurance companies in the next two subsections.

1. Solvency requirements pension funds

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 about 104.2%. 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.

2. Solvency requirements insurance companies

Instead of funding ratios, insurance companies compute solvency ratios to assess the solvency position. Solvency ratios equal the available capital divided by the required capital. Prior to the introduction of Solvency II in 2016, solvency ratios of insurance companies were not risk-based. The required eligible capital prior to 2016 equaled 4 percent of the value of the liabilities. At the introduction of Solvency II, the required capital is computed in a similar way as for pension funds, except that the required capital is calculated such that the probability that the funding ratio falls below 100 percent on a one-year horizon equals 0.5 percent, rather than the 2.5 percent for pension funds.

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 regulation solvency ratios equal $SR = \frac{A-L}{0.04L}$, which implies that the funding ratio equals $\frac{A}{L} = 0.04 * SR + 1$. The solvency ratios under Solvency II are more complex and hence I collect data on the assets and the liabilities for each insurer to compute the funding ratios manually.

D. 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 on average 80-90 percent in terms of AUM for all institutional investors domiciled in the Netherlands.[10]

I only analyze investors' direct holdings, that is, investments that are not made via other investor types such as mutual funds. The data, unfortunately, does not allow for a linkage between the indirect holdings of the investor to its 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 which allows me to use both their direct and indirect holdings.

E. Summary Statistics

This section briefly describes the summary statistics. Banks are the largest in terms of AUM, followed by life insurers and pension funds.[11] Life insurers and pension funds also have the highest bond duration of their fixed income portfolios. The average bond duration equals 11.3 and 10.6 years for life insurers and pension funds respectively, whereas this equals 4.3 years for banks, 7.3 for mutual funds and 6.3 for non-life insurers.

Life insurers and pension funds have the longest liability durations, equal to 11.0 and

[10] See for details on reporting requirements https://statistiek.dnb.nl/statistiek/index.aspx.
[11] Note that these summary statistics are based on the *direct* holdings only.

17.8 years respectively. The liability duration of non-life insurers is much shorter and equals 4.2 years. The average funding ratio of pension funds equals 109% and 110% for insurers. The heterogeneity in the funding ratios for pension funds is substantially larger than for insurers. Insurers generally hedge their liabilities more closely than pension funds because they face costs of financial distress, whereas pension funds cannot default.[12] Life insures and non-life insurers do not substantially deviate in terms of their solvency ratios.

[Place Table 2 about here]

V. Empirical methodology changes in holdings

I now turn to the testing of the empirical predictions from my theoretical framework in Subsection A, Subsection B, and Subsection C. As the regulatory change affected the pension and insurance sector only, I focus here on P&Is and come back to the other investor types in Section VI. For bond holdings, I use the *notional* values in all my analyses such that market prices are not driving the results. A change in notional values reflects active choices by investors, which is exactly the focus of this paper.

A. Long-term bond holdings and the regulatory discount curve

I now turn to the main regression specification. Even though the regulatory discount curve already affected interest rates as of maturities of 21 years, I focus here on long-term bonds with maturities of 30 years or longer. The weight assigned to the UFR is relatively small for the first affected maturities and these interest rates are closely linked to the 20 year interest rates and hence a good substitute to hedge the 20 year interest rate.

Figure 4 shows the average fraction of long-term bonds in the bond portfolio for P&Is over time. Following the two quarters after the UFR was implemented, there is a sharp

[12] In case a pension fund is not compliant with funding requirements, it files a recovery plan to the supervisor. Recovery measures may include an increase in contributions, a reduction of the future benefit accrual rate or, as a measure of last resort, a reduction of accrued benefits.

decline in long-term bond holdings for both life insurers and pension funds. Long-term bond holdings slightly increase again towards the end of 2014, but remain substantially lower than the pre-UFR levels.

[**Place Figure 4 about here**]

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

$$w^B_{it} = \alpha + \beta_0 \text{UFR}_t + \beta_1 \text{UFR}_t \times D^L_{2012q1,i} + \beta_2 \text{FR}_{it-1} + \beta_3 D^L_{it-1} + \nu_i + \epsilon_{it}, \tag{35}$$

where UFR_t equals one after implementation of the UFR and zero otherwise, $D^L_{2012q1,i}$ is the liability duration as of 2012q1, FR_{it-1} the lagged funding ratio, D^L_{it-1} the lagged liability duration, and ν_i are fund fixed effects.

Table 3 shows the results. P&Is with long liability durations decrease long-term holdings to a larger extent than the ones with short liability durations, supporting the first prediction of my theoretical framework in Section III. The effect is also economically significant. The average liability duration in the cross-section of P&Is equals 14 years, which implies long-term bond holdings decreased by approximately $14 \times 0.0018 = 2.5$ percent. The total decline in long-term bond holdings due to the regulatory change equals:

$$\sum_{i=1}^{N} \hat{\beta}_1 \times D^L_{2012q1,i} \times AUM^B_i = 15.30 \text{ billion}, \tag{36}$$

where AUM^B_i is the total AUM in bonds. The total AUM in long-term bonds prior to the regulatory change equals 36.10 billion, so this means a relative decrease of 42 percent.

Besides, to give additional support for the economic effects, P&Is invest 20 percent of the total bond portfolio in Dutch government bonds on average, which means a decline in these holdings of $25\% \times 15.30 = 3.06$ billion. The average amount outstanding of 30-year Dutch government bonds equals 14 billion, and hence, the total decline corresponds to 22 percent of its amount outstanding.[13]

Table 3 also shows the changes in bond holdings with maturities varying between 15 and 25 years, and maturities less than 15 years. P&Is increased their holdings towards bonds with maturities varying between 15 and 25 years, whereas they did not change their holdings to bonds with maturities less than 15 years. These results show that P&Is moved their long-term bonds with maturities of 30 years or longer to bonds with maturities around 20 years.

[Place Table 3 about here]

B. Long-term bond holdings and constraints

My model also predicts that P&Is closer to their solvency constraint decrease long-term bond holdings to a larger extent than funded P&Is. I use a triple difference-in-difference estimation technique to test this hypothesis:

$$w_{it}^{B} = \alpha + \beta_0 \text{UFR}_t + \beta_1 \text{UFR}_t \times D_{2012q1,i}^{L} \times \text{FR}_{2012q1,i}^{-1} + \beta_2 \text{FR}_{it-1}^{-1} + \beta_3 D_{it-1}^{L} + \nu_i + \epsilon_{it}, \quad (37)$$

where $FR_{2012q1,i}^{-1}$ is the inverse of the funding ratio as of 2012q1.

Table 4 summarizes the results. P&Is that are more constraint, i.e. 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 25 basis points, which is equivalent to 1.89 billion, or 5.26% of the long-term bond holdings. P&Is that are more constrained also increase their holdings towards

[13] As a robustness check, I have also added mutual funds to estimate (35): Mutual funds do not have liabilities and therefore their liability durations essentially equal zero. Including mutual funds to the sample with a liability duration forced to zero does not affect the sign and the magnitude of the coefficients.

bonds with maturities between 15 and 25 years to a larger extent than non-constrained ones.

[Place Table 4 about here]

C. Stock allocation and the regulatory discount curve

The final model implication for the changes in holdings is that P&Is closer to their solvency constraint allocate more of their assets to stocks at implementation of the UFR. I use the following difference-in-difference specification to test this hypothesis formally:

$$w_{it}^{S} = \alpha + \beta_0 \text{UFR}_t + \beta_1 \text{UFR}_t \times \text{FR}_{2012q1,i}^{-1} + \beta_2 \text{FR}_{it-1} + \nu_i + \epsilon_{it}. \quad (38)$$

Table 5 shows that more constrained P&Is increase their stock allocation to a larger extent. A one standard deviation increase in the inverse of the funding ratio (0.08) increases the stock allocation with 2.43%, which is equivalent to an average increase of 225 million that is allocated to stocks.

[Place Table 5 about here]

D. Derivative positions

The empirical analysis so far uses long-term bond holdings only. However, interest rate risk is also managed by using derivative contracts, especially for very long-term maturities. As of the start of 2012, pension funds have to mandatorily report interest rate derivative positions on an aggregate level: They report the market value of interest rate derivative contracts broken down in different types of derivative contracts. Moreover, they report the values of these positions after a parallel shock in interest rates of +1% (-1%) and +0.5% (-0.5%).[14]

[14] Unfortunately, insurance companies only started reporting derivative positions at the start of 2016 when Solvency II was introduced.

This allows me to compute the dollar durations of the derivative positions.[15] Because the data on derivative positions is available for only two quarters prior to the regulatory change, the time series is not long enough to statistically test if pension funds decreased their interest rate risk exposure via derivatives as well. However, using the time series of the cross-sectional average implied duration of the derivative portfolios, I show suggestive evidence that pension funds also substantially decreased their derivative positions after the regulatory change.

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

$$D^{\$}_{p,t} \approx -\frac{dV_t}{dr} = \frac{V_t^{-dr} - V_t^{+dr}}{|dr|} \tag{39}$$

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

Figure 5 depicts the cross-sectional average duration implied by the swap portfolio over time, where the duration is computed as the dollar duration in (39) relative to 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 multiplied by the allocation to fixed income. On average, pension funds have a balance sheet duration equal to 10 years. As the duration of the liabilities equals 18 years on average, this means that pension funds hedge approximately half of their interest rate risk. Importantly, the portfolio duration shows a sharp decline at the implementation of the UFR, consistent with the predictions of the model and the empirical findings for long-term bond holdings.

[Place Figure 5 about here]

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

VI. Bond yields and future excess returns

In this section, I test the empirical predictions of my model for yields and future excess returns. As opposed to the previous section, I use data on Dutch government bonds holdings only, because P&Is hold a substantial fraction of their assets in Dutch government bond bonds and hence price effects will be particularly visible for this subset of bonds. I start with the first prediction: future excess returns are higher when the P&I sector as a whole is underfunded. Then, I estimate the effect of the UFR on yields by using the construction of the UFR that affects yields at different maturities differently as an exogenous shock to demand. Finally, I 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). Their framework allows me to compute demand elasticities with respect to price, which, in turn, allow me to study the importance of various investor types in creating price effects.

A. Aggregate underfunding and future excess returns

My model predicts that future excess returns are lower if the P&I sector is more underfunded. Underfunding means that P&Is have less capital than the minimal required capital. If P&Is are underfunded, their demand for long-term bonds increases and hence the interest rate risk that has to be carried by myopic investors decreases, which in turn lowers expected future returns. To test this hypothesis formally, I determine the aggregate level of underfunding as the fraction of pension funds that are underfunded relative to the total at the end of a given quarter. The data is from the website of DNB.[16]

I use data from Bloomberg on the nominal Dutch yield curve to compute future excess returns. The log excess return is defined as in (6), minus the risk-free interest rate: $rx_{t+1}^{(h)} =$

[16] The data can be found here: https://statistiek.dnb.nl/en/dashboards/pensions/index.aspx. Because the solvency positions of insurers only go back till 2009, I use data on pension funds alone. Because the solvency positions of both insurers and pension funds are driven by the same factors, using aggregate pension fund data alone is sufficient. Robustness checks that use a weighted average of the solvency positions of pension funds and insurance companies indeed confirm this.

$y_t^{(h)} - (h-1)[y_{t+1}^{(h-1)} - y_t^{(h)}] - y_t^{(1)}$. Table 6 provides the summary statistics on the annual excess returns $rx_{t+1}^{(h)}$ for bonds with maturities 10, 20 and 30 years, together with summary statistics on the instantaneous forward rates f_t^h for $h = 1, 2, 3, 4, 5$.

[Place Table 6 about here]

Then, to formally test this model implication, I run the following regression:

$$rx_{t+1}^{(h)} = \alpha + \beta_0 UNF_t + \beta_1' x_t + \epsilon_{t+1}^{(h)}, \tag{40}$$

where $rx_{t+1}^{(h)}$ is the annual excess bond return from time t to time $t+1$ for a bond with maturity h, UNF_t equals the fraction of pension funds that are underfunded at time t, and x_t includes a set of controls.

Because I only observe the fraction of underfunded pension funds at a quarterly frequency, I estimate the regressions on a quarterly frequency.[17] This implies I forecast returns for every four quarters. I compute standard errors using the Newey and West (1987) standard errors that allow for serial correlation up to 6 lags. The controls include the term spread, following Campbell and Shiller (1991), or the first five forward rates, following Cochrane and Piazzesi (2005).

Table 7 shows the results of the forecasting regressions. Figure 6 plots the fraction of underfunded pension funds and the one-year ahead excess return on a 10-year bond. As the figure shows and the table confirms, a higher fraction of underfunded pension funds is associated with lower future excess returns. As expected, the effect is stronger for longer maturity bonds.

The economic magnitude of the effects are substantial. A one standard deviation increase in the fraction of underfunded pension funds (0.24) decreases the excess future returns with 8.24 percent. Assuming that the change in underfunded pension funds has no effect on

[17] The literature tends to use monthly data, however results of standard forecasting regressions using the term spread or forward rates do not substantially change when using a quarterly or a monthly frequency.

expected returns beyond a year, this corresponds to a decline in contemporaneous 30-year yields of 27 basis points (see Equation (27): 8.24%/30).[18] This equals 19 basis points for a 20-year bond and 12 basis points for a 10-year bond. As a robustness check, Table 16 and 17 of the Appendix summarize the results if I use the average percentage points of underfunding and the return on the liabilities as alternative proxies for the degree of underfunding. The effects using these alternative proxies are similar to the results discussed here.[19]

Running a regression of the aggregate allocation to fixed income on the level of underfunding indeed confirms that the fraction of underfunding increases the allocation to bonds: a one standard deviation increase in the fraction of underfunded pension funds increases the allocation to fixed income by 1.97%.[20]

Evidently, running a regression of returns on a proxy for demand does generally not allow to cleanly identify the causality between demand shocks and asset prices, because there could be omitted variables that drive demand for bonds and is correlated with the degree of underfunding (e.g. supply of bonds). Therefore I now turn to the asset pricing implications of the regulatory change that uses the construction of the UFR as an exogenous shock to demand.

[Place Table 7 about here]

B. Instrument to measure the effect of demand on yields

I start with estimating the effect of the UFR on yields. The standard approach to measure the effect of demand shocks on asset prices is to use event studies around key policy announcement days. A possible drawback of event studies is that investors may anticipate

[18] In untabulated regressions, I find that the forecasting power substantially decreases when predicting 5 quarter future excess returns and completely vanishes using 6 quarters or more.

[19] For the first proxy, the effect of a one standard deviation increase on the 30-year yield equals 32 basis points, whereas for the second proxy this effect equals 19 basis points. The effect of the second proxy is smaller because the degree of underfunding is largely determined by both the returns on equity and bonds, whereas the return on the liabilities is only picking up the latter part.

[20] Formally, I run the following regression: $w_t^{FI} = \alpha + \beta_0 UNF_t + \epsilon_t$. I find a coefficient on $\beta_0 = 0.0821$ with a t-stat equal to 3.73 with an $R^2 = 0.25$.

the regulatory change and expectations already adjust before the actual announcement. Alternatively, the response to the regulatory change may arrive with a delay. I therefore use an instrumental variable approach instead, in a similar way as in Koijen et al. (2020). Even though investors may have anticipated the UFR, the determinants of the shape of the UFR such as its level and the slope were largely unknown.[21]

I use the weights assigned to the UFR as an instrument for changes in demand. The weights assigned to the UFR for every maturity bucket are summarized in Table 15 of the Appendix. The instrumental variable is defined as $z_t(m) = \xi(m)D_t$, where $\xi(m)$ is the average weight assigned to the UFR for maturity bucket m and D_t equals one after implementation of the UFR and zero otherwise. I use seven maturity buckets and a summary of the instrument for each maturity bucket is given in Table 8.

[Place Table 8 about here]

The first-stage regression of the instrumental variable estimator equals:

$$y_t(m) = \beta_0 + \beta_1 z_t(m) + \beta_2' x_t(m) + \lambda_t + \epsilon_t(m), \tag{41}$$

where $y_t(m)$ is the average yield for maturity bucket m, $x_t(m)$ includes bond characteristics, and λ_t are time fixed effects. Safe, (long-term) government bond returns are primarily driven by duration and convexity. The vector of bond characteristics therefore includes the average duration of the bond in every maturity bucket and the average convexity, measured as the duration squared. I also include the average coupons. The time fixed effects are either measured by the 10-year German yield or by using time fixed effects.

The results are summarized Table 9. The coefficient for the instrument equals 0.397, with a standard error of 0.092. A coefficient of 0.397 implies that government bond yields with time-to-maturity between 21 and 25 years went up with 10 basis points, for time-to-maturities

[21] https://www.dnb.nl/en/news/news-and-archive/dnbulletin-2012/dnb276012.jsp

between 26 and 30 years with 23 basis points, and for time-to-maturities longer than 30 years with 36 basis points. This implies an increase in the 30-20 year spread of approximately 23 basis points. These estimates are larger than the estimates found in Greenwood and Vissing-Jorgensen (2018), who find an increase in the Dutch 30-10 year spread of 15 basis points by conducting an event study (Figure 3). Event studies only capture the immediate decrease in long-term bond holdings around the announcement of the regulatory change. However, P&Is did not sell everything at once, but instead spread out the decrease in long-term bond holdings over four quarters (Figure 4).

[Place Table 9 about here]

[Place Figure 3 about here]

C. The connection between portfolio holdings and yields

In this section, I connect investors' portfolio holdings to yields using the asset demand system developed by Koijen and Yogo (2019). Investor i's investment in Dutch government bonds with maturity bucket m is denoted by $H_{it}(m)$, and the investment in the outside asset is denoted by O_{it}.[22] Because I cannot observe what investors consider to be the outside asset, I use the 10-year German yield as proxy for the outside asset. German government bonds are important alternative liability hedge assets outside of the Netherlands.[23] The portfolio weight in the framework of Koijen and Yogo (2019) is then defined as:

$$w_{it}(m) = \frac{H_{it}(m)}{O_{it} + \sum_{m=1}^{M=7} H_{it}(m)} = \frac{\delta_{it}(m)}{1 + \sum_{m=1}^{M=7} \delta_{it}(m)}, \tag{42}$$

where $\delta_{it}(m) = H_{it}(m)O_{it}^{-1}$ and $w_{it}(0) = 1 - \sum_{m=1}^{M=7} w_{it}(m)$ equals the fraction invested in the outside asset. Demand for government bonds with maturity m is a function of bond

[22] The results do not materially change using all bonds outside of the Netherlands as the outside asset.
[23] However, the results are robust using other proxies for the outside asset.

yields and characteristics:

$$\ln \delta_{it}(m) = \alpha_i + \beta_{0i} y_t(m) + \beta_{1i}' x_t(m) + \beta_{2i} \ln H_i^{2009q2}(m) + \beta_{3i} y_t^{DE} + \epsilon_{it}(m), \tag{43}$$

where $H_i^{2009q2}(m)$ equals the initial holdings in each maturity bucket m and y_t^{DE} the 10-year German yield.

Koijen and Yogo (2019) show that (43) 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 expected returns and factor loadings are affine in a set of characteristics. The set of characteristics is similarly defined as in (41). In addition, I also add the initial holdings of investors to capture persistent unobserved investor type characteristics. The component of demand that is not captured by prices, characteristics, and time-invariant characteristics, $\epsilon_{it}(m)$, is referred to as latent demand. The German yield y_t^{DE} captures alternative liability hedge opportunities outside of the Netherlands.

As in Koijen et al. (2020), I assume that holdings of the outside asset move only due to changes in the German yield:

$$O_{it} = O_i \exp(\psi_i y_t^{DE}). \tag{44}$$

Equation (45) can then be written as:

$$\begin{aligned} \ln H_{it}(m) &= \ln \delta_{it}(m) + \ln O_{it} \\ &= \hat{\alpha}_i + \beta_{0i} y_t(m) + \beta_{1i}' x_t(m) + \beta_{2i} \ln H_i^{2009q2}(m) + \hat{\beta}_{3i} y_t^{DE} + \epsilon_{it}(m), \end{aligned} \tag{45}$$

where $\hat{\alpha}_i = \alpha_i + \ln O_i$ and $\hat{\beta}_{3i} = \beta_{3i} + \psi_i$.

In order to obtain consistent estimates of the parameters in (45) using OLS one has to assume that characteristics are exogenous to latent demand. However, 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, where I use the instrument as specified in the previous subsection, Equation (41). The first stage of the instrumental variable approach is summarized in column (1) of Table 10. The F statistic equals 11.37 and is substantially 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, suggesting that the instrument is not weak.

I estimate the demand curves for banks, insurance companies, mutual funds, pension funds, and the foreign sector. I first show the results aggregated by investor type as I do not have investor specific characteristics for all types in my sample that would allow me 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 by the other sectors, where the data on the total amount outstanding is from the Dutch State Treasury Agency.[24]

Columns 2-6 of Table 10 show the estimates of the demand system. P&Is have demand curves that are upward sloping, which is consistent with my model. Because of duration mismatch between the assets and the liabilities, a decrease in interest rates decreases the funding ratio. From (16), we observe that a low funding ratio increases the demand for long-term bonds. Foreign investors prefer shorter duration bonds, whereas P&Is prefer longer duration bonds, consistent with Section V. Moreover, P&Is prefer bonds with higher coupons, potentially resulting from the desire to match the cash flows of their liabilities. In all cases, the initial holdings are positive and statistically significant, meaning that unobserved time-invariant characteristics explain a substantial part of the holdings.

[Place Table 10 about here]

I can use the demand system to connect prices to elasticity of demand with respect to price for all investor types. Koijen and Yogo (2019) and Koijen et al. (2020) show that price

[24] https://english.dsta.nl

elasticity of demand is equal to:

$$\frac{\partial q_{it}(m)}{\partial p_{it}(m)} = 1 + 100\frac{\beta_{0i}}{T_{mt}}(1 - w_{it}(m)), \tag{46}$$

where lowercase are log of variables and T_{mt} is the average maturity for maturity bucket m. To compute $w_{it}(m)$, I use the investment in euro area bonds except Dutch ones as the outside asset.

The demand elasticities with respect to price for each investor type are summarized in Table 12. A demand elasticity close to zero implies that demand is inelastic and a large value implies that demand is sensitive to the price. Banks have the highest demand elasticity, followed by mutual funds and the foreign sector. However, the estimate for banks is very imprecise. Banks are not holding the longest maturity bonds and therefore the instrument is weak. Consistent with the findings before, demand elasticities are negative for the P&I sector. The weighted average elasticity equals 2.05 and the weight of each sector is computed as the average weights of the different investor types in each maturity bucket prior to the implementation of the UFR. The weights of each sector are summarized in Table 11. As in Koijen et al. (2020), demand elasticities are substantially higher than the estimates for stock markets, e.g. Chang et al. (2015) find an elasticity close to one. However, the average weighted price elasticity of demand is lower than measured in Koijen et al. (2020), where the unit of observation are the holdings of government debt in a particular country. This means that investors are less price elastic across maturity buckets than they are across countries. Government bonds issued by (some) countries in the euro area may be closer substitutes than bonds of different maturities from a balance sheet perspective.

In order to derive pricing effects from the demand system, I can perform a simple back-of-the-envelope calculation. Pension funds and insurers sold 22 percent of the amount outstanding of 30-year Dutch government bonds. The weighted average price elasticity of demand equals 2.05 and thus the price effect equals $22\%/2.05 = 10.73\%$. For a bond with a maturity of 30 years, this implies an increase in long-term yields of 36 basis points, which is close to the price effect found in subsection B.

[Place Table 11 about here]

[Place Table 12 about here]

D. Demand curves P&Is including characteristics

My model predicts that the demand for bonds depends primarily on the liability structure and solvency positions of P&Is. My model predicts that demand for long-term bonds is higher when liability duration is longer as well as when the funding ratio is low. In this section, I extend the framework of Koijen and Yogo (2019) by also including two key P&Is characteristics: the liability duration and the solvency position. In this setting, demand for government bonds with maturity m becomes a function of bond yields, bond characteristics, and fund characteristics interacted with bond characteristics:

$$\begin{aligned} \ln H_{it}(m) &= \hat{\alpha}_i + \beta_{0i} y_t(m) + \beta'_{1i} x_t(m) + \beta'_{2i}(x_{1t}(m) \times v_{it}) \\ &+ \beta_{3i} \ln H_i^{2009q2}(m) + \hat{\beta}_{4i} y_t^{DE} + \epsilon_{it}(m) \end{aligned} \tag{47}$$

where v_{it} includes the liability duration and the solvency position for investor i at time t, $x_t(m)$ includes bond characteristics as defined before, and $x_{1t}(m)$ includes bond duration and convexity, and α_i includes investor fixed effects. Again, I include the initial holdings as well as the 10-year German yield.

Table 13 shows the results for insurers. On average, insurance companies with long liability durations prefer bonds with long durations, but relatively low convexity. This means that insurance companies prefer long-term bonds, but not the bonds with the longest maturities. The UFR creates incentives to hedge the duration of the liabilities, but less so the convexity of the liabilities, i.e. the cash flows at the very long-end of the maturity spectrum. I also compute the demand system for insurers with high versus low liability durations and high and low solvency positions, respectively. Interestingly, insurers with long liability durations have much stronger upward sloping demand curves than average, whereas insurers with low liability durations have neither upward nor downward sloping demand curves. Moreover, insurers with low solvency positions have slightly stronger upward sloping demand curves than insurers with high solvency positions, again consistent with the predictions of my model.

[Place Table 13 about here]

Table 14 shows the results for pension funds. Pension funds with long liability durations generally have a preference for bonds with long liability durations but lower convexity, as for insurance companies. There is some evidence that pension funds with high solvency positions have a stronger preference for bonds with high convexity, consistent with the finding in B that pension funds with high solvency positions decreased long-term bond holdings to a smaller extent than the ones with low solvency positions. As opposed to insurance companies, pension funds with long versus short liability do not differ as much in the slope of their demand curves. Notice, however, that the heterogeneity in liability durations is much smaller for pension funds than for insurers.

[Place Table 14 about here]

VII. Conclusion

In this paper, using holdings data and price data simultaneously, I study changes in hedging incentives of long-term investors and its effect on asset prices. My findings suggest that regulation plays an nontrivial role in the demand for long-term bonds which, in turn, affect the asset prices of these bonds. This has important policy implications as these findings can be used to design long-term investor regulation in a way that is desirable for the economy as a whole. In particular, my findings show the relevance of incorporating the regulatory framework of long-term investors to analyze effects of conventional and unconventional monetary policy.

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Appendix

A. Further details on UFR

The UFR was initially discussed as part of the Long-Term Guarantee Assessment (LTGA) of Solvency II regulation. EIOPA proposed the regulatory discount curve based on the UFR method first in 2010. There are three important decisions policy makers 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%, which is based on 2% expected inflation and 2.2% 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 curve at which the UFR method starts was set at 20 years and the convergence period is set at 40 years. The extrapolation method proposed by EIOPA is the Smith-Wilson technique. The Smith-Wilson technique only uses the forward rates at time-to-maturity 19 to 20 years and the UFR to compute the yield curve.

For pension funds a slight modification was used, namely the market interest rates at each maturity in combination with the UFR. For pension funds, the convergence is such that its a weighted average between market interest rates and the UFR. So as opposed to insurers, not only the forward rate from time-to-maturity 19 to 20 years is used, but the implied market forward rate for each maturity and the UFR.

B. Model derivation

This appendix solves the optimization problems of P&Is. The mean-variance optimization problem equals:

$$
\begin{aligned}
\max_{w_t} \quad & \mathbb{E}[u(\frac{A_{t+1}}{A_t} - \frac{L_{t+1}}{A_t})] \\
= \quad & \arg\max_{w_t} \mathbb{E}[\frac{A_{t+1}}{A_t}] - \frac{\gamma}{2}\mathrm{Var}[\frac{A_{t+1}}{A_t} - \frac{L^E_{t+1}}{A_t}] - \frac{\lambda(F^R_t)}{2}\mathrm{Var}[\frac{A_{t+1}}{A_t} - \frac{L^R_{t+1}}{A_t}],
\end{aligned}
\tag{48}
$$

subject to

$$
w_t'\iota = w_t^S + w_t^B\iota \leq 1, \tag{49}
$$

$$
w_t^S, w_{h,t}^B \geq 0 \qquad \forall h, \tag{50}
$$

The Lagrange equals:

$$
\begin{aligned}
\mathcal{L}(w_t, \nu_t, \delta_t) &= R_f + w_t'\mathbb{E}_t[r_{t+1} - r_f] \\
&- \frac{\gamma}{2}\Big(w_t'\mathrm{Var}_t[r_{t+1}]w_t + a_t'\mathrm{Var}_t[r^B_{t+1}]a_t\frac{1}{F^E_t} - 2w_t'\mathrm{Cov}_t[r_{t+1}, r^B_{t+1}]a_t\frac{1}{F^E_t}\Big) \\
&- \frac{\lambda(F^R_t)}{2}\Big(w_t'\mathrm{Var}_t[r_{t+1}]w_t + (\xi_L \circ a_t)'\mathrm{Var}_t[r^B_{t+1}](\xi_L \circ a_t)\frac{1}{F^R_t} \\
&- 2w_t'\mathrm{Cov}_t[r_{t+1}, r^B_{t+1}](\xi_L \circ a)\frac{1}{F^R_t}\Big) + \nu_t(w_t'\iota - 1) + \delta_t'w_t.
\end{aligned}
\tag{51}
$$

Taking the derivative with respect to w_t^S, w_t^B, and ν_t gives:

$$
\frac{\partial\mathcal{L}(w_t^S, \nu_t, \delta_t^S)}{\partial w_t^S} = \mathbb{E}_t[r^S_{t+1} - r_f] - (\gamma + \lambda(F^R_t))\mathrm{Var}_t[r^S_{t+1}]w_t^S + \nu_t + \delta_t^S = 0, \tag{52}
$$

$$\frac{\partial \mathcal{L}(w_t^B, \nu_t, \delta_t^B)}{\partial w_t} = \mathbb{E}_t[r_{t+1}^B - r_f] - (\gamma + \lambda(F_t^R))\text{Var}_t[r_{t+1}^B]w_t^B - \gamma \text{Var}_t[r_{t+1}^B]a_t \frac{1}{F_t^E} - \lambda(F_t^R)\text{Var}_t[r_{t+1}](\xi_L \circ a_t)\frac{1}{F_t^R} + \nu_t \iota = 0, \tag{53}$$

$$\frac{\partial \mathcal{L}(w_t, \nu_t, \delta_t)}{\partial \nu_t} = w_t' \iota - 1 = 0. \tag{54}$$

This results in the optimal weights (15) and (16):

$$w_t^{S*} = \underbrace{\frac{\mathbb{E}_t[r_{t+1}^S - r_f] + \nu_t + \delta_t^S}{(\gamma + \lambda(F_t^R))\text{Var}_t[r_{t+1}^S]}}_{\text{speculative portfolio}} \tag{55}$$

$$w_t^{B*} = \underbrace{\frac{\mathbb{E}_t[r_{t+1}^B - r_f] + \nu_t \iota + \delta_t^B}{(\gamma + \lambda(F_t^R))\text{Var}_t[r_{t+1}^B]}}_{\text{speculative portfolio}} + \underbrace{\frac{\gamma}{\gamma + \lambda(F_t^R)} a_t \frac{1}{F_t^E}}_{\text{economic hedging portfolio}} + \underbrace{\frac{\lambda(F_t^R)}{\gamma + \lambda(F_t^R)}(\xi_L \circ a_t)\frac{1}{F_t^R}}_{\text{regulatory hedging portfolio}}. \tag{56}$$

with ν_t (if the constraint binds):

$$\nu_t = \frac{1 - \left(\frac{\mathbb{E}_t[r_{t+1}^S - r_f] + \delta_t^S}{(\gamma+\lambda(F_t^R))\text{Var}_t[r_{t+1}^S]} + \left(\frac{\mathbb{E}_t[r_{t+1}^B - r_f] + \delta_t^B}{(\gamma+\lambda(F_t^R))\text{Var}_t[r_{t+1}^B]}\right)'\iota + \left(\frac{\gamma}{\gamma+\lambda(F_t^R)} a_t \frac{1}{F_t^E}\right)'\iota + \left(\frac{\lambda(F_t^R)}{\gamma+\lambda(F_t^R)}(\xi_L \circ a_t)\frac{1}{F_t^R}\right)'\iota \right)}{\left(\frac{\iota}{(\gamma+\lambda(F_t^R))\text{Var}_t[R_{t+1}]}\right)'\iota}. \tag{57}$$

C. Computation of bond durations

In this appendix I explain the computation of bond durations for various bond types. I compute durations of zero coupon and STRIPS as the difference between the maturity T and the current time t, the duration of floating rate bonds as the difference between current time t and the next coupon payment date, and the duration of a perpetual bond as c_s/r, where c_s the coupon-rate for security s. I compute fixed coupon bond durations provided that the yield-to-maturity is given, as follows:

$$D_{s,t} = \sum_{n=1}^{N} n \times \frac{\frac{CF_{s,t+n}}{(1+y_{s,t})^n}}{\sum_{n=1}^{N} \frac{CF_{s,t+n}}{(1+y_{s,t})^n}} \tag{58}$$

where $y_{s,t}$ the yield-to-maturity of security s at time t, $CF_{s,t+n} = c_s$ for $n = 1, ..., N-1$ and $CF_{s,t+N} = 100 + c_s$, with c_s the coupon-rate for security s.

In case the yield-to-maturity is not available, but maturity dates and coupons are given, I compute the duration as follows:

$$D_{s,t} = \sum_{n=1}^{N} n \times \frac{\frac{CF_{s,t+n}}{(1+r_t^n)^n}}{\sum_{n=1}^{N} \frac{CF_{s,t+n}}{(1+r_t^n)^n}} \tag{59}$$

where r_t^n is the interest rate at time t with maturity n. I use the European yield curve from the ECB's website at each time t to compute the durations.[25]

[25] The durations based on yield-to-maturity or the yield curve produce very similar results.

Figure 1. **Regulatory discount curve**

This graph shows the economic discount curves (solid red line) and the regulatory discount curve (dashed green line) at implementation of 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 $\triangle y = -1\%$.

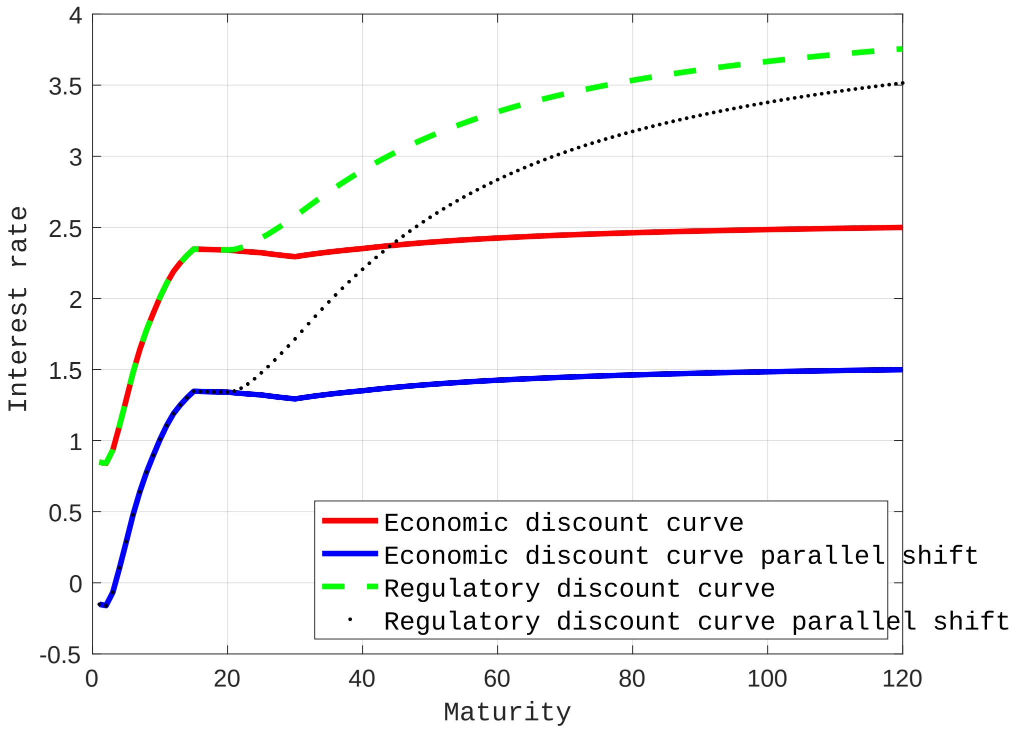

Figure 2. **Cash flows of pension payments**

This graph shows the cash flows of pension payments (*not* discounted) for an average pension fund in million euros.

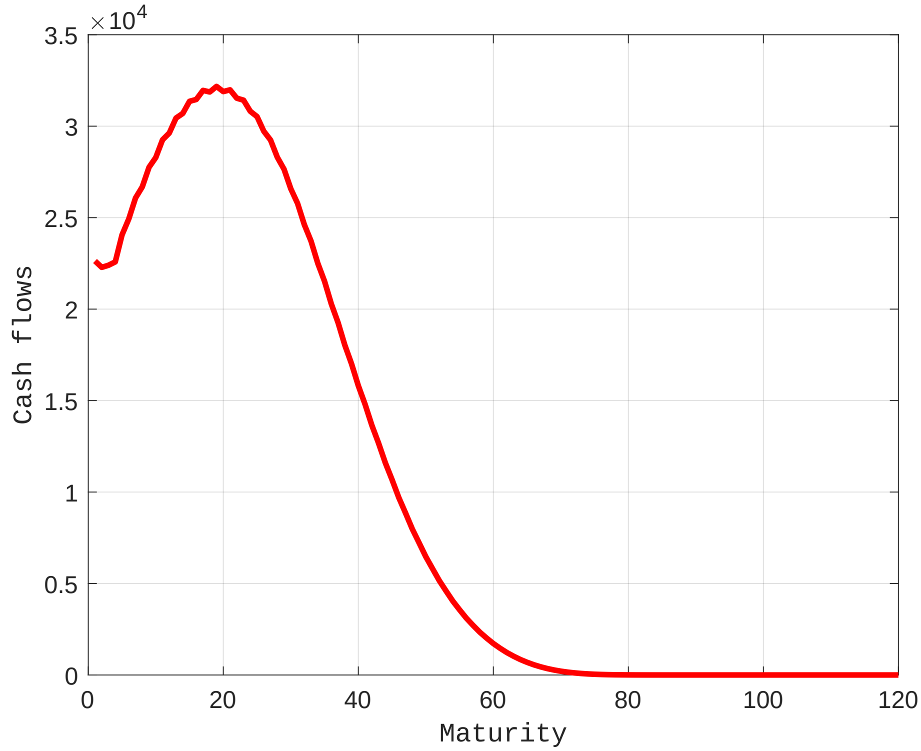

Figure 3. **Government bond yield spreads**

This graph shows the spread between 30 year and 20 year Dutch government bonds. The vertical lines are three days before and after the announcement of the UFR.

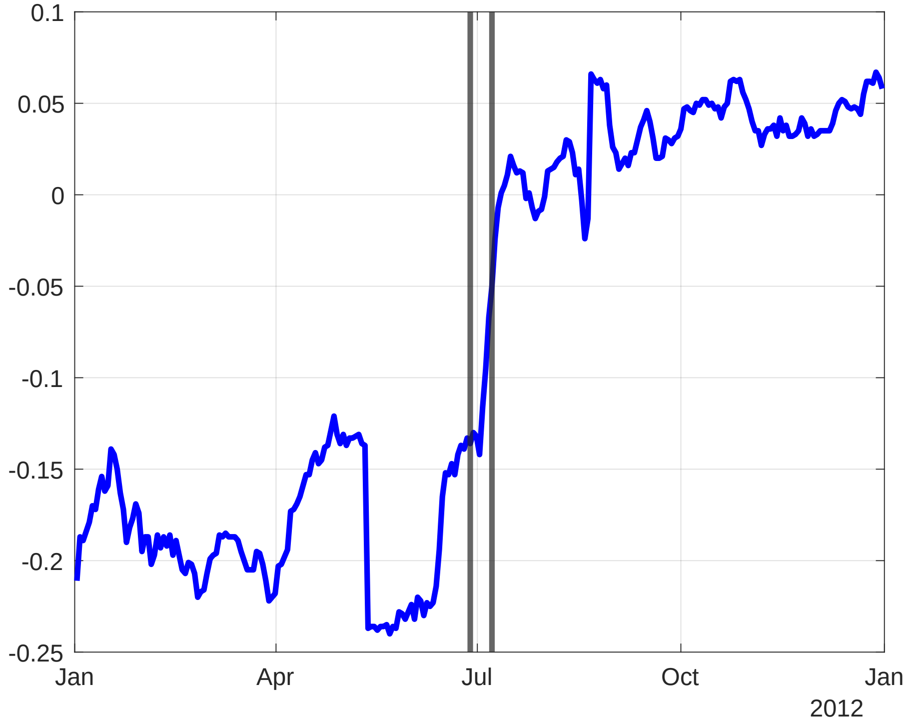

Figure 4. **Long-term bond holdings by institutional investor type**

This graph shows the average fraction of bonds with a maturity of 30 years or longer for life insurers, non-life insurers, and pension funds over the period 2009q1-2018q1.

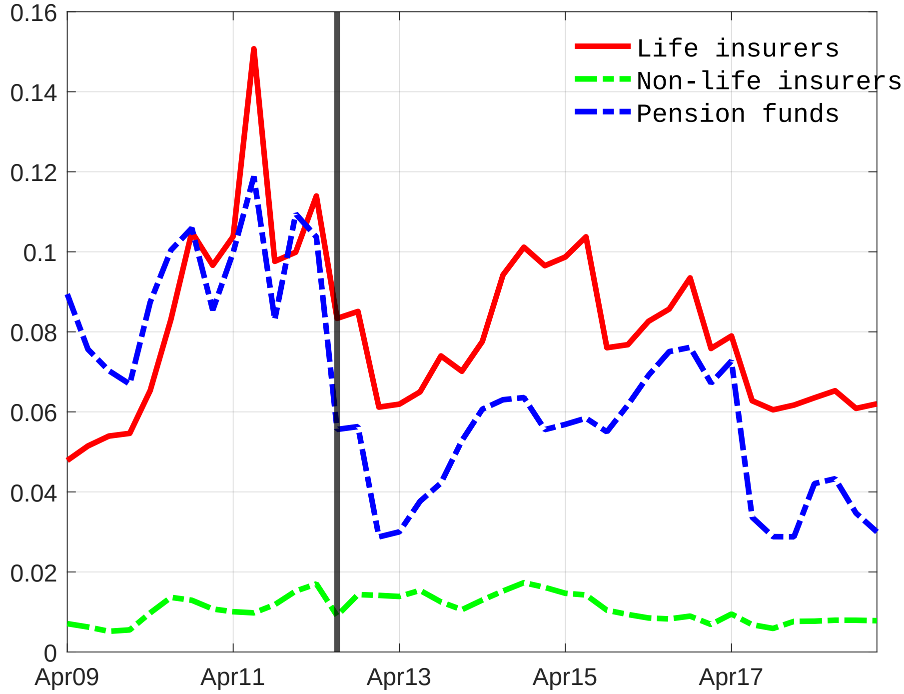

Figure 5. **Implied duration of pension funds' portfolios**

This graph shows the relative implied duration of the swap portfolio and the duration of the total portfolio of pension funds. The (relative) 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 relative implied duration of the swap portfolio and the duration of the fixed income portfolio times the allocation to fixed income.

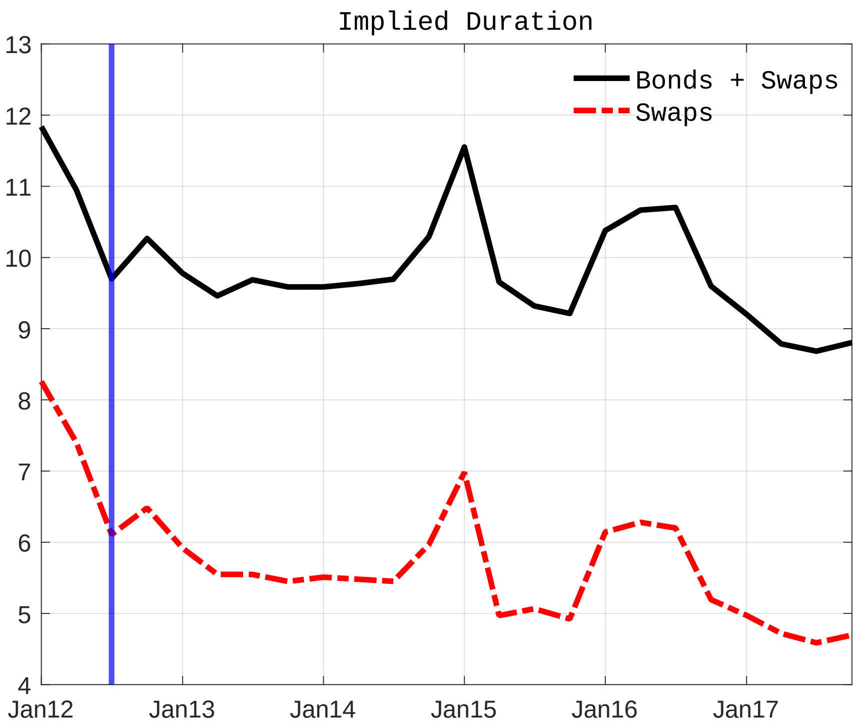

Figure 6. **Future excess returns and underfunded pension plans**

This graph shows the one year future excess return and the fraction of underfunded pension plans or the liability return ($r_t^L = \frac{L_t - L_{t-1}}{L_{t-1}}$). The upper figure shows the excess returns (percentage points) on the left y-axis and the fraction of underfunded pension plans (percent) on the right y-axis. The lower figure shows both the excess returns and liability return on the left y-axis (percentage points).

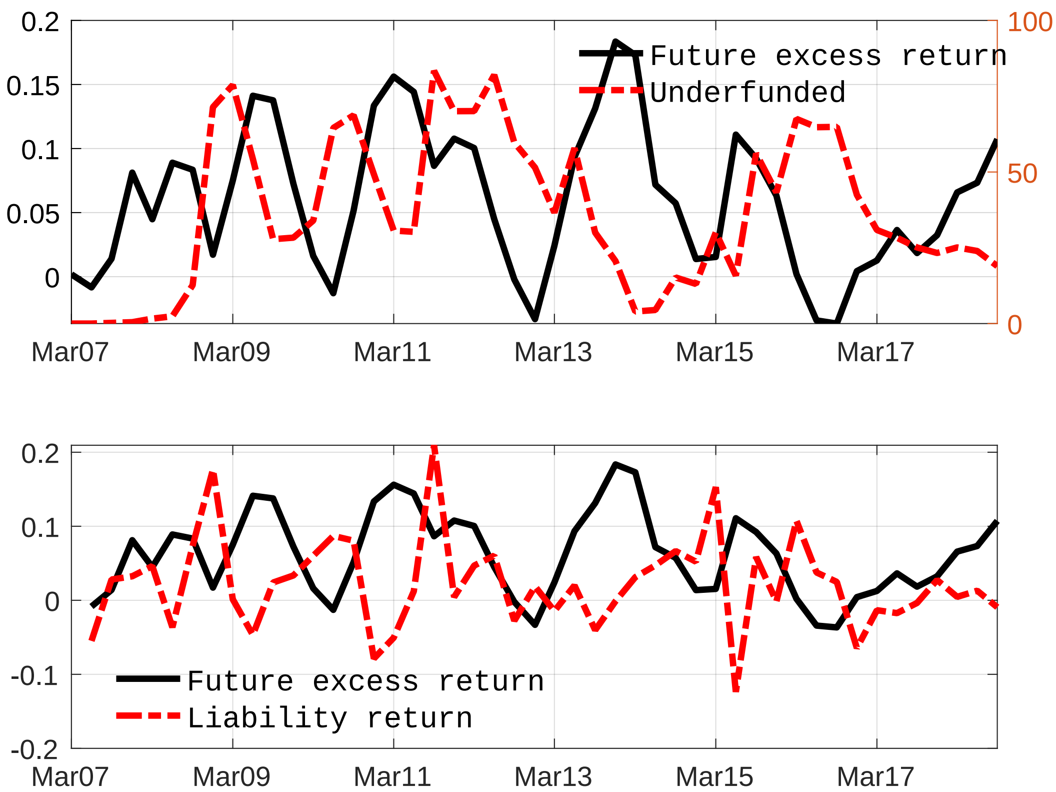

Table 1. **Value liabilities with and without UFR**: This table shows the value of the liabilities with and without UFR for an average pension fund in my sample on September 30, 2012. The table also shows the liability value after a parallel shock in interest rates of −1%. The liability values are computed for all projected cash flows and for cash flows with maturities longer than 20 years only. The relative change computes the percentage drop in the liability value due to implementation of the UFR. The values are in million euros.

Cash flows all maturities	without UFR	with UFR	relative change
Discounted value liabilities	16360	15696	−4.23%
Discounted value liabilities $\triangle r = -1\%$	19878	18433	−7.84%
Change value liabilities	3518	2737	−28.52%
Cash flows maturities $T > 20$	without UFR	with UFR	relative change
Discounted value liabilities	6694	6030	−11.01%
Discounted value liabilities $\triangle r = -1\%$	9155	7711	−18.74%
Change value liabilities	2461	1680	−46.5%

Table 2. **Summary statistics**: This table shows the following summary statistics: total AUM of directly reported assets (AUM), AUM in bonds (AUM bonds), AUM in stocks (AUM stocks), bond duration (Bond duration), liability duration (Liability duration), and the solvency positions (Funding ratio). The funding ratio is in percentage points, AUM in million euro, bond and liability duration in years. Equity mutual funds are excluded from the sample.

AUM	mean	std.dev.	p50	AUM bonds	mean	std.dev.	p50
Banks	20,695	26,558	8,893	Banks	19,591	25,185	8,893
Life insurers	19,917	17,695	21,534	Life insurers	14,557	13,788	13,594
Non-life insurers	1,383	1,332	831	Non-life insurers	1,112	1,237	650
Mutual funds	763	1,422	432	Mutual funds	622	853	371
Pension funds	14,760	39,731	4,322	Pension funds	7,876	20,143	2,450
AUM stocks	**mean**	**std.dev.**	**p50**	**Bond duration**	**mean**	**std.dev.**	**p50**
Banks	1,104	3,291	9	Banks	4.3	3.5	3.7
Life insurers	5,360	4,644	3,743	Life insurers	11.3	3.5	11.4
Non-life insurers	271	417	117	Non-life insurers	6.3	4.1	6.2
Mutual funds	141	668	145	Mutual funds	7.3	4.8	6.8
Pension funds	6,884	20,197	1,851	Pension funds	10.6	3.7	10.4
Liability duration	**mean**	**std.dev.**	**p50**	**Funding ratio**	**mean**	**std.dev.**	**p50**
Life insurers	11.0	3.5	11.7	Life insurers	110	4	109
Non-life insurers	4.1	2.8	3.5	Non-life insurers	110	5	108
Pension funds	17.8	2.9	17.6	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 (35): $w^B_{it} = \alpha + \beta_0 \text{UFR}_t + \beta_1 \text{UFR}_t \times D^L_{2012q1,i} + \beta_2 \text{FR}_{it-1} + \beta_3 D^L_{it-1} + \nu_i + \epsilon_{it}$, with UFR equal to 1 as of 2012Q1 and zero otherwise, $D^L_{2012q1,i}$ the duration of the liabilities as of 2012Q1, and controls include the lagged inverse of the funding ratio and the liability duration. 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. ICL is a dummy that equals one for life insurers and zero otherwise and PF equals one for pension funds and zero otherwise. Robust standard errors are in parentheses; $^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$.

	Holdings $T \geq 30$		Holdings $15 \leq T \leq 25$		Holdings $T \leq 15$	
UFR	0.0115		−0.0361**		0.0514	
	(0.0080)		(0.0160)		(0.0317)	
UFR × D^L_{2012q1}	−0.0023***	−0.0018***	0.0033***	0.0034***	−0.0014	−0.0028
	(0.0007)	(0.0007)	(0.0012)	(0.0012)	(0.0021)	(0.0022)
1/Funding ratio	0.0418	0.0431	−0.1371**	−0.1324	0.0335	0.0471
	(0.0359)	(0.0480)	(0.0684)	(0.0939)	(0.1054)	(0.1447)
Liability duration	0.0030*	0.0064***	0.0026	0.0029	−0.0085	−0.0219***
	(0.0017)	(0.0023)	(0.0027)	(0.0039)	(0.0055)	(0.0065)
ICL	0.0370*		0.0324		−0.0934	
	(0.0199)		(0.0337)		(0.0724)	
PF	0.0043		0.0187		−0.0448	
	(0.0273)		(0.0432)		(0.0899)	
Fund FE	No	Yes	No	Yes	No	Yes
Time FE	No	Yes	No	Yes	No	Yes
N	2,376	2,376	2,376	2,376	2,376	2,376
R^2	0.11	0.61	0.15	0.66	0.16	0.73

Table 4. **Long-term bond holdings and constraints**: This table present the results of the regression described in Equation (**??**): $w_{it}^B = \alpha + \beta_0 \text{UFR}_t + \beta_1 \text{UFR}_t \times D^L_{2012q1,i} \times \text{FR}^{-1}_{2012q1,i} + \beta_2 \text{FR}^{-1}_{it-1} + \beta_3 D^L_{it-1} + \nu_i + \epsilon_{it}$, with UFR equal to 1 as of 2012Q1 and zero otherwise, $D^L_{2012q1,i}$ the duration of the liabilities as of 2012Q1, and controls include the lagged inverse of the funding ratio and the liability duration. 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. ICL is a dummy that equals one for life insurers and zero otherwise and PF equals one for pension funds and zero otherwise. Robust standard errors are in parentheses; $^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$.

	Holdings $T \geq 30$		Holdings $15 \leq T \leq 25$		Holdings $T \leq 15$	
UFR	0.0128		-0.0378^{**}		0.0599^{*}	
	(0.0088)		(0.0160)		(0.0327)	
UFR $\times D^L_{2012q1} \times$	-0.0027^{***}	-0.0021^{**}	0.0039^{***}	0.0040^{***}	-0.0023	-0.0037
$\text{FR}^{-1}_{2012q1,i}$	(0.0009)	(0.0009)	(0.0012)	(0.0013)	(0.0025)	(0.0025)
1/Funding ratio	0.0341	0.0317	-0.1266^{*}	-0.1090	0.0199	0.0137
	(0.0332)	(0.0446)	(0.0680)	(0.0948)	(0.1009)	(0.1394)
Liability duration	0.0032^{*}	0.0065^{***}	0.0025	0.0028	-0.0079	-0.0210^{***}
	(0.0019)	(0.0023)	(0.0027)	(0.0038)	(0.0054)	(0.0064)
ICL	0.0360^{*}		0.0325		-0.0944	
	(0.0200)		(0.0336)		(0.0720)	
PF	0.0028		0.0192		-0.0493	
	(0.0271)		(0.0429)		(0.0895)	
Fund FE	No	Yes	No	Yes	No	Yes
Time FE	No	Yes	No	Yes	No	Yes
N	2,349	2,349	2,349	2,349	2,349	2,349
R^2	0.11	0.61	0.15	0.67	0.15	0.72

Table 5. **Stock allocation and the regulatory discount curve**: This table present the results of the regression described in Equation (): $w^S_{it} = \alpha + \beta_0 \text{UFR}_t + \beta_1 \text{UFR}_t \times \text{FR}^{-1}_{2012q1,i} + \beta_2 \text{FR}_{it-1} + \nu_i + \epsilon_{it}$, with UFR equal to 1 as of 2012Q1 and zero otherwise, $FR^{-1}_{2012q1,i}$ the inverse of the funding ratio as of 2012Q1, and the control includes the lagged inverse of the funding ratio. 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. ICL is a dummy that equals one for life insurers and zero otherwise and PF equals one for pension funds and zero otherwise. Robust standard errors are in parentheses; $^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$.

	Equity allocation	
UFR	−0.2073	
	(0.1406)	
UFR × $\text{FR}^{-1}_{2012q1,i}$	0.2646*	0.3042**
	(0.1601)	(0.1558)
1/Funding ratio	−0.0289	0.0751
	(0.0859)	(0.1160)
ICL	0.0773	
	(0.0869)	
PF	0.1919***	
	(0.0554)	
Fund FE	No	Yes
Time FE	No	Yes
N	2,407	2,407
R^2	0.16	0.86

Table 6. **Summary statistics Dutch yields**: This table presents the means, medians standard deviations, minimum, and maximum of Dutch zero-coupon government bond yields. Panel A shows the summary statistics on Dutch yields, where the data is from Bloomberg and covers the period 2007-2020. Panel B presents the summary statistics on the measures for aggregate underfunding. All reported numbers are in percentage points, except the fraction of underfunded pension plans which is in percent. rx_{t+1}^{h} is the excess return for a bond with maturity h, y_t^h is the yield for a bond with maturity h, $f_t^{(h)}$ is the instantaneous forward rate for a bond with maturity h.

	mean	median	std.dev.	min	max	N
Panel A: Dutch zero-coupon government bond yields (%)						
rx_{t+1}^{10}	5.31	5.16	6.08	-5.73	18.35	48
rx_{t+1}^{20}	8.11	8.66	13.19	-14.06	41.56	48
rx_{t+1}^{30}	10.37	9.63	19.43	-23.05	61.34	48
$y_t^{10} - y_t^1$	1.43	1.25	0.84	0.03	3.09	48
$f_t^1 (= y_t^1)$	0.60	0.01	1.56	-0.78	4.65	48
f_t^2	1.27	0.72	1.67	-0.79	4.80	48
f_t^3	1.70	1.47	1.72	-0.68	4.82	48
f_t^4	2.03	1.92	1.68	-0.55	4.55	48
f_t^5	2.34	2.45	1.60	-0.33	4.72	48
Panel B: Underfunded pension plans						
1. Fraction underfunded (percent)	37	31	24	0	83	48
2. Level underfunded (%)	2.12	0	3.26	0	12.2	48
3. Liability return (%)	2.62	2.61	6.13	-12.37	20.95	48
$\rho(1,2)$	0.84					
$\rho(1,3)$	0.33					
$\rho(2,3)$	0.46					

Table 7. **Forecasting excess bond returns using the fraction of underfunded pension plans**: This table presents the regressions of the future 4-quarter excess returns on the fraction of underfunded pension plans: $rx_{t+1}^{(h)} = \alpha + \beta_0 UNF_t + \beta_1' x_t + \epsilon_{t+1}^{(h)}$. The regressions are estimated with quarterly data from 2007 until 2019q4. I forecast the excess return each quarter for the following 4 quarters. I use Newey and West 1987 standard errors to correct for the overlapping nature of the regressions (parentheses), with a total of 6 lags. Controls include the term spread (Campbell and Shiller 1991) and the first five instantaneous foward rates (Cochrane and Piazzesi 2005). $^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$.

	30-year			20-year			10-year		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
UNF_t	−35.677***	−34.324***	−57.786***	−15.807*	−15.937*	−33.201***	−4.135	−5.657*	−10.896***
	(10.811)	(10.795)	(6.639)	(8.563)	(8.555)	(5.291)	(3.522)	(3.363)	(2.689)
$y_t^{(10)} - y_t^{(1)}$		2.467			2.201			1.737*	
		(3.730)			(2.511)			(0.984)	
$f_t^{(1)}$			−13.397***			−12.117***			−4.991***
			(4.506)			(2.811)			(1.519)
$f_t^{(2)}$			3.504			6.441			4.031
			(9.513)			(6.920)			(3.571)
$f_t^{(3)}$			−5.338			−3.225			−2.902
			(7.709)			(4.843)			(2.887)
$f_t^{(4)}$			5.062			2.537			3.017
			(11.943)			(6.332)			(3.400)
$f_t^{(5)}$			8.823			5.203			0.904
			(13.566)			(7.909)			(3.887)
N	48	48	48	48	48	48	48	48	48
R^2	0.22	0.18	0.49	0.10	0.08	0.51	0.03	0.07	0.43

Table 8. **Instrument for every maturity bucket**: This table shows the instrument for every maturity bucket used for the instrumental variable approach in Section VI. The instrument is constructed as the average weight assigned to the UFR for each maturity bucket. An overview of the weights for every maturity is given in Table 15.

	$[0,5]$	$(5,10]$	$(10,15]$	$(15,20]$	$(20,25]$	$(25,30]$	$(30,\infty)$
ξ_m	0	0	0	0	0.263	0.579	0.910

Table 9. **Measuring the effect of demand on yields**: This table presents regression results of the yields on the instrument for demand: $y_t(m) = \beta_0 + \beta_1 z_t(m) + \beta_2' x_t(m) + \lambda_t + \epsilon_t(m)$, where $z_t(m)$ is the instrument. The instrument is constructed as the average weight assigned to the UFR for each maturity bucket (Table 8). The controls $x_t(m)$ include the average bond duration, convexity, and coupon for each maturity bucket m. I also control for time effects by using the 10-year German yield or time fixed effects. Robust standard errors are in parentheses; $^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$.

	$z_t(m)$	Duration	Convexity	Coupon	10-year yield	Quarter FE	R^2	N
$y_t(m)$	0.334^{***}	0.241^{***}	-0.007^{***}	0.034^{**}	1.011^{***}	No	0.97	243
	(0.111)	(0.015)	(0.001)	(0.015)	(0.014)			
$y_t(m)$	0.397^{***}	0.249^{***}	-0.007^{***}	0.017		Yes	0.98	243
	(0.092)	(0.016)	(0.001)	(0.012)				

Table 10. **Demand system**: This table shows the regression results of the demand system described in (43): $\ln H_{it}(m) = \hat{\alpha}_i + \beta_{0i} y_t(m) + \beta'_{1i} x_t(m) + \beta_{2i} \ln H_i^{2009q2}(m) + \hat{\beta}_{3i} y_t^{DE} + \epsilon_{it}(m)$. The first column shows the first stage regression for the foreign investors. The instrument $z_t(m)$ equals the weights assigned to the UFR for every maturity bucket m, described in Table 8. The controls $x_t(m)$ include the average bond duration, convexity, coupon, and initial bond holdings for each maturity bucket m. Robust standard errors are in parentheses; $^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$.

	$y_t(m)$	Holdings Banks	Holdings Foreign	Holdings IC	Holdings MF	Holdings PF
$y_t(m)$		2.171	1.156**	−2.639**	0.531**	−1.640***
		(3.493)	(0.559)	(1.205)	(0.258)	(0.632)
$z_t(m)$	0.435***					
	(0.088)					
Duration	0.168***	0.405	−0.730***	0.910***	−0.289	0.523***
	(0.034)	(0.568)	(0.127)	(0.286)	(0.296)	(0.130)
Convexity	−0.006***	−0.019	0.019***	−0.028***	−0.011	−0.014***
	(0.001)	(0.016)	(0.003)	(0.007)	(0.008)	(0.003)
Coupon	−0.021	−0.079	−0.267***	0.375***	0.013	0.106***
	(0.017)	(0.092)	(0.050)	(0.049)	(0.015)	(0.035)
Initial holdings	−0.192***	0.361***	0.129	1.654***	0.895***	0.773***
	(0.062)	(0.089)	(0.222)	(0.253)	(0.122)	(0.113)
10-year German yield	1.019***	2.079	−1.409	2.795	−1.366	2.361**
	(0.015)	(3.544)	(0.878)	(1.725)	(1.930)	(0.967)
N	243	209	243	243	243	243
R^2	0.98	0.68	0.55	0.28	0.75	0.41

Table 11. **Weights of investor types in each maturity bucket**: This table shows the weights of the investor types (banks, insurance companies, foreign investors, mutual funds, and pension funds) at the start of 2012q1. The fraction of foreign investors is determined as the fraction of total amount outstanding that is not held by one of the Dutch institutions. The column tot. (tot. long) defines the total fraction that each investor is holding relative to the total amount outstanding (total amount outstanding maturities exceeding 10 years).

	$[0,5]$	$(5,10]$	$(10,15]$	$(15,20]$	$(20,25]$	$(25,30]$	$(30,\infty)$	tot.	tot. long
Banks	3	16	2	9	3	4	0	9	4
Foreign investors	90	70	75	52	44	42	49	75	52
Insurers	3	6	12	21	29	30	27	8	24
Mutual funds	1	1	1	2	1	1	1	1	1
Pension funds	3	7	10	16	23	23	23	9	19

Table 12. **Price elasticity of demand**: This table shows the price elasticity of demand, computed as in Equation (46). The average, standard deviation, minimum, and maximum over time are given. Total elasticity is the weighted average elasticity, using the weights of each sector defined in Table 11.

	obs.	mean	std.dev.	min	max
Banks	209	23.93	25.57	5.67	83.88
Foreign investors	243	4.53	1.89	1.84	11.28
Insurance companies	243	−29.95	31.68	−102.44	−6.93
Mutual funds	243	8.30	6.82	1	22.23
Pension funds	243	−18.61	20.19	−63.63	−3.97
Total	2.05				

Table 13. **Demand system with insurer characteristics** This table shows the results of the demand system including insurers characteristics (liability duration and solvency ratio) described in (47): $\ln B_{it}(m) = \hat{\alpha}_i + \beta_{0i} y_t(m) + \beta'_{1i} x_t(m) + \beta'_{2i}(x_{1t}(m) \times v_{it}) + \hat{\beta}_{3i} y_t^{DE} + \alpha_i + \epsilon_{it}(m)$. The first column shows the first stage regression. The instrument $z_t(m)$ equals the weights assigned to the UFR for every maturity bucket m, described in Table 8. The results are reported for all insurers, as well as insurers that are above the 70th percentile or below the 30th percentile of the liability duration (solvency ratio). The 30th and 70th percentile are determined in each quarter. Controls include the bond characteristics, the 10-year German yield, and the initial holdings. Robust standard errors are in parentheses; $^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$.

	$y_t(m)$	Holdings all	Holdings high dur	Holdings low dur	Holdings high FR	Holdings low FR
$y_t(m)$		-2.432^{***}	-3.903^{***}	1.300	-3.138^{***}	-3.714^{**}
		(0.697)	(1.340)	(1.568)	(0.984)	(1.837)
$z_t(m)$	0.435^{***}					
	(0.088)					
bond dur × liability dur		0.011^{***}	-0.032^{***}	-0.020^{*}	0.020^{***}	0.016^{***}
		(0.001)	(0.007)	(0.012)	(0.003)	(0.003)
bond convex × liability dur		-0.001^{***}	0.002^{***}	0.003^{***}	-0.001^{***}	-0.001^{***}
		(0.000)	(0.000)	(0.001)	(0.000)	(0.000)
bond dur × solvency ratio		−0.003	0.002	0.019	−0.008	0.075
		(0.004)	(0.027)	(0.012)	(0.008)	(0.054)
bond convex × solvency ratio		0.000	−0.001	-0.002^{**}	0.001	−0.002
		(0.000)	(0.002)	(0.001)	(0.001)	(0.003)
Controls	Yes	Yes	Yes	Yes	Yes	Yes
N	243	3,418	848	1,105	910	1,066
R^2	0.98	0.68	0.44	0.68	0.68	0.63

Table 14. **Demand system with pension fund characteristics** This table shows the results of the demand system including pension fund characteristics (liability duration and funding ratio) described in (47): $\ln B_{it}(m) = \hat{\alpha}_i + \beta_{0i} y_t(m) + \beta'_{1i} x_t(m) + \beta'_{2i}(x_{1t}(m) \times v_{it}) + \hat{\beta}_{3i} y_t^{DE} + \alpha_i + \epsilon_{it}(m)$. The first column shows the first stage regression. The instrument $z_t(m)$ equals the weights assigned to the UFR for every maturity bucket m, described in Table 8. The results are reported for all pension funds, as well as pension funds that are above the 70th percentile or below the 30th percentile of the liability duration (funding ratio). The 30th and 70th percentile are determined in each quarter. Controls include the bond characteristics, the 10-year German yield, and the initial holdings. Robust standard errors are in parentheses; $^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$.

	$y_t(m)$	Holdings all	Holdings high dur	Holdings low dur	Holdings high FR	Holdings low FR
$y_t(m)$		-0.565^{*}	-1.038	-0.284	-1.844^{***}	-1.685^{*}
		(0.323)	(0.777)	(0.508)	(0.507)	(0.994)
$z_t(m)$	0.456^{***}					
	(0.087)					
bond dur × liability dur		0.007^{***}	0.013^{***}	0.019^{***}	0.004^{*}	-0.016^{***}
		(0.001)	(0.005)	(0.005)	(0.002)	(0.004)
bond convex × liability dur		-0.0002^{***}	-0.001^{***}	-0.001^{**}	-0.000	0.001^{***}
		(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
bond dur × funding ratio		-0.032	0.141	-0.078	-0.217^{**}	0.080
		(0.043)	(0.099)	(0.076)	(0.102)	(0.222)
bond convex × funding ratio		0.001	0.008	0.002	0.010^{**}	0.001
		(0.002)	(0.006)	(0.004)	(0.005)	(0.013)
Controls	Yes	Yes	Yes	Yes	Yes	Yes
N	243	6,085	1,580	2,115	1,980	1,497
R^2	0.98	0.40	0.53	0.38	0.41	0.46

Appendix

Table 15. **Weights UFR in regulatory discount curve**: This table shows the weights assigned to the UFR to compute the regulatory discount curve. The weights are derived using the Smith-Wilson technique.

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	0.970
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 16. **Forecasting excess bond returns using the percentage points of underfunding**: This table presents the regressions of the future 4-quarter excess returns on the percentage points of underfunding ($\min(0, FR_t - 104.2)$): $rx_{t+1}^{(h)} = \alpha + \beta LUNF_t^L + \beta' x_t + \epsilon_{t+1}^{(h)}$. The regressions are estimated with quarterly data from 2007 until 2019q4. I forecast the excess return each quarter for the following 4 quarters. I use Newey and West 1987 standard errors to correct for the overlapping nature of the regressions (parentheses), with a total of 6 lags. Controls include the term spread (Campbell and Shiller 1991) and the first five instantaneous forward rates (Cochrane and Piazzesi 2005). $^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$.

	30-year			20-year			10-year		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
$LUNF_t$	-2.941^{***}	-2.932^{***}	-3.100^{***}	-1.416^{***}	-1.476^{***}	-1.648	-0.415^{*}	-0.503^{**}	-0.530^{***}
	(0.572)	(0.573)	(0.332)	(0.475)	(0.455)	(0.216)	(0.235)	(0.222)	(0.123)
$y_t^{(10)} - y_t^{(1)}$		-0.140			0.917			1.325	
		(3.459)			(2.524)			(1.076)	
$f_t^{(1)}$			-9.154^{**}			-9.562^{***}			-4.124^{***}
			(4.379)			(2.885)			(1.508)
$f_t^{(2)}$			10.869			10.777			5.445
			(12.043)			(8.337)			(3.980)
$f_t^{(3)}$			-7.144			-4.808			-3.456
			(8.784)			(5.522)			(2.917)
$f_t^{(4)}$			-6.943			-4.972			0.533
			(14.578)			(8.983)			(4.446)
$f_t^{(5)}$			13.570			8.956			2.183
			(19.517)			(12.343)			(5.526)
N	48	48	48	48	48	48	48	48	48
R^2	0.27	0.27	0.41	0.14	0.15	0.40	0.06	0.09	0.37

Table 17. **Forecasting excess bond returns using the return on liabilities**: This table presents the regressions of the future 4-quarter excess returns on the liability return ($\frac{L_t - L_{t-1}}{L_{t-1}}$): $rx^{(h)}_{t+1} = \alpha + \beta r^L_t + \beta' x_t + \epsilon^{(h)}_{t+1}$. The regressions are estimated with quarterly data from 2007 until 2019q4. I forecast the excess return each quarter for the following 4 quarters. I use Newey and West 1987 standard errors to correct for the overlapping nature of the regressions (parentheses), with a total of 6 lags. Controls include the term spread (Campbell and Shiller 1991) and the first five instantaneous forward rates (Cochrane and Piazzesi 2005). $^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$.

	30-year			20-year			10-year		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
r^L_t	−1.001***	−0.950***	−0.809**	−0.582**	−0.579**	−0.440**	−0.231**	−0.252**	−0.172
	(0.313)	(0.318)	(0.332)	(0.231)	(0.231)	(0.217)	(0.117)	(0.114)	(0.106)
$y^{(10)}_t - y^{(1)}_t$		−2.466			−0.123			1.043	
		(4.007)			(2.832)			(1.169)	
$f^{(1)}_t$			−4.086			−6.862*			−3.239*
			(6.430)			(3.915)			(1.776)
$f^{(2)}_t$			7.756			9.076			4.759
			(13.874)			(9.205)			(4.244)
$f^{(3)}_t$			−11.720			−7.152			−3.947
			(13.488)			(6.901)			(2.544)
$f^{(4)}_t$			−15.353			−9.408			−0.792
			(18.130)			(10.863)			(5.221)
$f^{(5)}_t$			26.670			15.830			4.128
			(20.781)			(13.300)			(6.223)
N	47	47	47	47	47	47	47	47	47
R^2	0.11	0.12	0.22	0.08	0.08	0.28	0.06	0.12	0.32