Life Insurance Convexity*

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Abstract

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Abstract

Life insurers sell savings contracts with surrender options, which allow policyholders to prematurely receive guaranteed surrender values. These surrender options move toward the money when interest rates rise. Hence, higher interest rates raise surrender rates, as we document empirically by exploiting plausibly exogenous variation in monetary policy. Using a calibrated model, we then estimate that surrender options would force insurers to sell up to 2% of their investments during an enduring interest rate rise of 25 bps per year. We show that these fire sales are fueled by surrender value guarantees and insurers' long-term investments.

1 Introduction

Life insurers are significant financial intermediaries, as they hold 20% of outstanding bonds (IMF, 2021) and their products account for more than 20% of households' assets.[1] An important role of life insurers is to facilitate household saving by offering long-term savings contracts. These contracts typically entail surrender options, which allow policyholders to terminate a contract before its maturity and receive an ex ante guaranteed redemption value, termed *surrender value*.[2] When market interest rates rise, surrender options move toward the money. This paper quantifies the resulting effects on the life insurance sector's liquidity and spillovers to financial markets.

First, we provide empirical evidence for a causal effect of interest rates on life insurance surrender. The estimate implies that a 1 percentage point (ppt) increase in long-term government bond rates raises surrender rates, i.e., the share of life insurance contracts surrendered, by 25 basis points (bps). Thus, surrender options contribute to the *interest rate convexity* of life insurance contracts, i.e., their duration declines when interest rates increase.

Second, we develop a structural model of policyholders' surrender decisions and embed it into a granular model of a representative life insurer's cash flows. Numerical simulations of the calibrated model show that elevated surrender rates during an enduring interest rate rise of 25 bps per year would force insurers to sell nearly 2% of their assets annually. Because insurers are among the largest groups of investors, especially in bond markets, surrender-

[1] Life insurance and annuities account for 14.8% and 5.1% of U.S. households' assets, respectively (*Source: U.S. Census Wealth and Asset Ownership for Households: 2018*). Life insurance and pension funds account for more than 30% of European households' financial assets (*Source: ECB Statistical Data Warehouse*).

[2] *Surrender* is closely related to *lapse* in life insurance. Lapses are contract terminations upon policyholders' failure to pay premiums, whereas surrenders typically refer to active terminations in exchange for a positive surrender value (e.g., see `https://www.newyorklife.com/articles/glossary`).

driven asset sales can have a significant price impact, about 40 bps in our model.

Third, we use counterfactual calibrations to explore determinants of forced asset sales. Important determinants are the long duration of insurers' investments, which boosts the exercise value of surrender options when interest rates rise, and the guarantee on surrender values, which amplifies the interest rate sensitivity of surrender incentives. Although asset-liability duration matching has a small effect on the total volume of asset sales, it has a large effect on their timing and allocation across bond maturities.

Policymakers have only recently started to consider the liquidity risk driven by surrender options, focusing especially on an environment with increasing interest rates (e.g., ECB, 2017; EIOPA, 2019; NAIC, 2021).[3] For example, in early 2023, the Italian life insurer *Eurovita* was placed under special administration and its surrender payments were halted by the regulator because rising interest rates amplified the risk of high surrender rates (Fitch Wire, 2023a). Despite policymakers' increasing awareness, research on liquidity risk in life insurance is still scarce.

Three motivating facts emphasize the importance of surrender-driven liquidity risk and asset sales. First, surrender payouts are economically significant. European life insurers paid out EUR 362 billion for surrendered contracts in 2019, which corresponds to more than 40% of their premium income. Second, insurers are important investors. In euro-area debt markets, insurers account for roughly 20% of outstanding government and corporate bonds (ECB, 2022). Given the importance of bond prices for economic activity (Gilchrist

[3] For example, Mario Draghi, then president of the ECB, emphasizes in his introductory statement to the European Parliament on November 26, 2018, that *"[...] there might be times when policyholders want to terminate their insurance policies in large numbers, thereby putting liquidity strain on insurers. Authorities should be able to protect financial markets [...] from the adverse impact of such an exceptional run on insurers."*. Following policymakers, we focus on surrenders and their impact on life insurers' free cash flow as a main determinant of their liquidity risk.

and Zakrajšek, 2012; Kubitza, 2023), it is thus important to understand the determinants of insurers' investment behavior. In the most extreme case that European insurers financed the surrender payouts of 2019 entirely by selling assets, the associated price impact would be in the order of 3.6% ($= 362/10,000$), assuming that prices decline by 10 bps per EUR 10 billion of assets sold as in Greenwood et al. (2015). This magnitude is substantial, especially in bond markets, and it would further increase with higher surrender rates. Thus, surrender-driven asset sales have a potentially significant impact on financial markets and, thereby, on financial stability, especially when pressure to sell correlates with the financial cycle. Third, we present anecdotal evidence from historical episodes in which interest rate hikes have drained life insurers' liquidity. Despite this evidence, little is known about the impact of surrenders on life insurers' liquidity risk and asset sales across the financial cycle.

We address this void using the German life insurance market as a laboratory. German life insurers hold more than EUR 1 trillion in life insurance reserves, corresponding to roughly one third of German GDP. The most popular life insurance product in Germany is a participating contract, whose cash an insurer invests in a single portfolio of assets. Participating contracts account for 90% of life insurance reserves and, by regulation, include surrender options with ex ante guaranteed surrender values. Because life insurers mostly invest in long-term bonds, rising interest rates depress the market value of their assets, but not surrender values. Then, surrender becomes more attractive for policyholders as it allows them to exchange their claim on the depreciated assets for the guaranteed surrender value, e.g., to invest in alternative assets or substitute debt.

To empirically explore this channel, we combine printed and digital records of the German supervisor to construct a panel of annual insurer-level surrender rates covering all German life insurers since 1996. We regress surrender rates on the 10-year German government bond rate, controlling for macro-economic conditions. The estimate implies that a 1 ppt increase in the interest rate is associated with a 25 bps increase in the surrender rate. The economic magnitude is large: a one standard deviation interest rate increase corresponds to an increase in total German surrender payouts of roughly EUR 2.3 billion. A positive correlation between surrender and market interest rates is well-documented in prior studies (e.g., Koijen et al., 2022). However, it may be biased by unobserved economic conditions that affect both surrender and interest rates, such as government policies, as well as by the impact of surrender-driven changes in insurers' investment behavior. We address these concerns in two steps. First, we focus on the economic mechanism by exploring the interaction between interest rates and the guaranteed minimum return on life insurance contracts. The larger the guaranteed return, the less interest-rate sensitive are surrender incentives. Accordingly, we find that the correlation between surrender and interest rates significantly weakens with larger guaranteed returns.

Second, we strengthen the causal identification by exploiting U.S. monetary policy surprises as an instrumental variable for German government bond rates. Monetary policy surprises, measured as the change in short-term interest rates in a short time window around announcements of the Federal Open Market Committee (FOMC), isolate unexpected variation in monetary policy from economic fundamentals (Gertler and Karadi, 2015; Jarocínski and Karadi, 2020). Focusing on U.S. monetary policy surprises mitigates both potential omitted variable bias and reverse causality since German life insurers hold very little U.S. treasuries. Coefficients using the instrumental variable approach are similar to OLS estimates in terms of magnitude and significance, supporting a causal interpretation.

Armed with this empirical evidence, the second part of this paper quantifies the risk of surrender-driven asset sales during an interest rate rise. For this purpose, we develop a structural model of policyholders' surrender decisions, which we embed in a detailed, quantitative model with a dynamic, stochastic financial market and a representative life insurer's cash flows. Our calibration accounts for insurers' legacy business, which is important to appropriately capture cash flow dynamics. The financial market model features a stochastic short rate as in Vasicek (1977) as well as government and corporate bonds differing by maturity and credit rating.

We simulate paths with a length of 10 years, among which we select the 5% with the strongest interest rate rise. The average annual change in the 10-year interest rate among these interest rate rise paths is 25 bps, which corresponds to the 75th percentile of annual changes in German long-term rates from 1980 to 2019. In our model, rising interest rates drive up surrender rates to close to 12% after 10 years of rising rates. Associated surrender payments slowly drain the insurer's free cash flow until, after 7 years, they force the insurer to sell assets. The longer the interest rate rise lasts, the more assets the insurer sells each year. Total sales reach nearly 3% of invested assets after 10 years of rising interest rates. Using counterfactual calibrations with interest-rate-*in*sensitive surrenders, we find that surging surrender rates account for the majority (two-thirds) of asset sales.

Due to the systematic nature of an interest rate rise, it has broad effects on European life insurers. To provide an estimate of aggregate asset sales and price pressure, we scale our model to the size of European life insurance reserves with similar characteristics, which account for more than half of the European market. Following Greenwood et al. (2015) in calibrating insurers' price impact, surrender-driven asset sales reduce asset prices by 40 bps after 10 years of rising interest rates. This magnitude is plausible compared to empirical studies of fire sales, and it is economically significant, especially in the bond market.

In counterfactual calibrations, we explore the sensitivity of our results. We find that insurers' long-term investments are an important driver of surrender-driven asset sales. A long asset duration isolates the insurer's book-value investment return and, hence, also the policyholders' contract return from interest rate changes. For this reason, the longer the duration of insurers' investments, the longer it takes contract returns to increase after interest rates have started to rise. The resulting gap between contract returns and market interest rates strengthens surrender incentives. Consistent with this mechanism, we estimate that an increase in asset duration from 7.4 to 11.2 years relates to an increase in the total volume of asset sales from below 0.5% to above 2% of invested assets in an average year.

Moreover, we explore the impact of insurers' investment strategy. The baseline calibration assumes that the asset duration is held constant, which ensures that the results are not driven by changes in the investment portfolio. However, insurers typically match the duration of their assets to that of insurance contracts (Domanski et al., 2015; Ozdagli and Wang, 2020). We implement such duration matching in a counterfactual calibration. Our results imply that the total amount of asset sales is then similar to that in the baseline calibration. However, the timing and composition of asset sales change substantially. In the baseline calibration, the insurer sells mostly short-term bonds in later years to keep an overall long duration. Instead, under duration matching, the insurer sells mostly long-term bonds as soon as interest rates rise to reduce duration. Thus, insurers' investment strategy has important consequences for the impact of surrender-driven asset sales on the slope of the yield curve and their timing: with constant (liability-matching) asset duration, asset sales increase short-term (long-term) yields, flattening (steepening) the yield curve.

Finally, we discuss policy implications and means to mitigate the interest rate sensitivity of surrender rates. We show that reducing surrender value guarantees by adjusting surrender values to current interest rates can mitigate insurers' asset sales during an interest rate rise. We discuss the advantages and disadvantages of such market value adjustments over other policy tools, such as surrender penalties and the suspension of surrender payouts.

Liquidity risk has long been acknowledged as an important driver of financial fragility. Previous literature has traditionally focused on banks (starting with Diamond and Dybvig, 1982) and, more recently, mutual funds (Goldstein et al., 2017). Whereas the surrender options embedded in most life insurance contracts resemble withdrawal options of deposit contracts, life insurers differ from other financial institutions in many aspects, such as their regulation and offering of long-term guarantees (Koijen and Yogo, 2022a; Ellul et al., 2022). The significant size of life insurers and their pivotal role in fixed-income markets (Koijen and Yogo, 2022b; Butler et al., 2023) warrant a detailed understanding of their funding structure. However, while a growing literature examines insurers' investment behavior (Becker and Ivashina, 2015; Girardi et al., 2021; Becker et al., 2022; Jansen, 2021; Murray and Nikolova, 2022) and funding structure (Chodorow-Reich et al., 2020; Foley-Fisher et al., 2020; Coppola, 2022; Knox and Sørensen, 2023), research on liquidity risk in life insurance is scarce.

In theory, surrender options move toward the money when interest rates increase (Albizzati and Geman, 1994; Chang and Schmeiser, 2022).[4] This mechanism gives rise to the *interest rate hypothesis*, namely that higher interest rates lead to higher surrender rates. In-

[4]Insurers may profit from offering surrender options because policyholders often underestimate future liquidity needs (Gottlieb and Smetters, 2021).

deed, previous studies find a positive correlation between interest and surrender rates (Kuo et al., 2003; Eling and Kiesenbauer, 2014; Koijen et al., 2022). However, this estimated correlation may be confounded by unobserved economic conditions and by the impact of surrender-driven changes in insurers' investment behavior. We contribute to the literature by offering evidence for a *causal* impact of interest rates on surrender rates.

The interest rate hypothesis points to *life insurance convexity*, namely that the duration of life insurance contracts decreases with rising rates. This has important consequences for insurers' investment behavior. Ozdagli and Wang (2020) document that the duration of life insurers' asset investments negatively correlates with interest rates and argue that this relationship is due to the interest rate sensitivity of surrenders. Förstemann (2021) examines strategic complementarities in surrender options, which give rise to non-fundamental surrenders upon severe interest rate hikes, i.e., "insurance runs". We contribute to these studies by quantifying the effects of rising interest rates in an empirically calibrated, dynamic model of a representative insurer's cash flows and balance sheet. In contrast to Förstemann (2021), we focus on surrenders that are entirely driven by fundamentals. The model sheds light on the interactions of market interest rates, insurers' investments, surrenders, and asset sales. Thereby, we provide new insights for monetary policy and systemic risk of non-bank intermediaries.

The surrender-driven interest rate convexity in life insurance resembles the prepayment-driven convexity in fixed-rate mortgages (Chernov et al., 2018; Boyarchenko et al., 2019; Diep et al., 2021). In the latter case, an increase in long-term interest rates makes prepayments less favorable and, thereby, increases the duration of mortgage-backed securities (Hanson, 2014). Thus, convexity in mortgages is reversed to that in life insurance, which is an important insight for understanding the allocation of interest rate risk in the financial system.

Our paper also relates to recent studies about the role of long-term asset investments, e.g., in facilitating risk sharing (Hombert et al., 2021; Hombert and Lyonnet, 2022) and riding out short-term market fluctuations (Timmer, 2018; Chodorow-Reich et al., 2020). Our results emphasize that long-term investments can *increase* liquidity risk as they fuel surrender-driven asset sales when interest rates rise, pointing to potential costs of long-term investments.

Furthermore, we contribute to studies on fire sales in financial markets (e.g., Ellul et al., 2011; Greenwood et al., 2015; Lou and Wang, 2018; Nanda et al., 2019; Wang et al., 2020; Massa and Zhang, 2021). The most closely related study is Ellul et al. (2022), who present a model in which fire sales result from insurers' desire to replenish capital ratios by selling risky bonds after an exogenous income shock. Complementing this mechanism, in our model, surrenders directly affect insurers' cash flows and, therefore, can force them to sell assets.

2 Institutional Background

Savings and annuity contracts dominate the life insurance business, accounting for three quarters of all life insurance contracts in Germany (GDV, 2020). At retirement, policyholders can convert savings and annuity contracts into a lump sum payout or a stream of annuity payments. Before retirement, policyholders typically pay periodic premiums, which are invested by the insurer. In Europe, and especially in Germany, more than 60% of European life insurance reserves are *participating contracts*, whose cash is invested by the insurer in a joint portfolio.[5]

Surrender options, which allow policyholders to terminate a contract before maturity, are included in the majority of contracts, accounting for 88% of European life insurance reserves (EIOPA, 2019). In many cases, the associated surrender value is guaranteed, especially among participating contracts. The overall share of European life insurance contracts with surrender guarantees is thus substantial and corresponds to close to 60% of reserves (EUR 5 trillion in 2019).[6]

Within Europe, the provision of surrender guarantees is especially pronounced in Germany, where they apply to nearly 90% of savings and annuity reserves (GDV, 2020). The reason is that the vast majority of German life insurance contracts are participating (88% of reserves in 2019). Regulation mandates these contracts to offer a guaranteed surrender value equal to the accumulated cash value (i.e., book value) less administrative costs (German insurance contract law, Section 169). Moreover, since German insurers guarantee a minimum annual return on policyholders' savings, surrender values are bounded from below at contract origination already.

Total surrender payouts in 2019 were EUR 362 billion in the European Economic Area, of which EUR 21.5 billion were in Germany. Surrender payouts comprise almost half of insurers' cash outflows, as they correspond to 44% of all life insurance payouts. The relative

[5] Throughout the paper, we use data on the balance sheet of German and European insurers based on European Solvency II reporting at the single insurer (solo) level at quarterly frequency, downloaded from EIOPA's website in September 2020 (`http://eiopa.europa.eu/`). The U.S. life insurance market exhibits a stronger focus on nonparticipating policies, which allow policyholders to choose investment strategies (Koijen and Yogo, 2022a). We discuss surrender options in U.S. life insurance in Internet Appendix A.

[6] Among participating contracts with surrender option, the surrender value is almost always guaranteed (for 91% of corresponding reserves), while it is less common among nonparticipating contracts with surrender option (23% of corresponding reserves) (EIOPA, 2019, Table 3). Using that the share of participating contracts is 63% in 2019, the share of European life insurance reserves with guaranteed surrender value is $58\% = 88\% \cdot (91\% \cdot 63\% + 23\% \cdot 37\%)$.

size of surrender payouts is similar when comparing them to total premiums, which are insurers' main cash inflows. Even when accounting for other cash flows (insurers' investment income, insurance benefits, and expenses), surrender payouts remain a significant share of the resulting net cash flow, for example, 24% in Germany.[7] Thus, surrender payouts are a significant determinant of life insurers' liquidity.

In Internet Appendix B, we describe three historical episodes, during which surrender rates sharply responded to rising interest rates and significantly drained life insurers' liquidity. More recently, since euro-area interest rates started to rise significantly in 2022, life insurers are facing large increases in surrender payouts, "highlighting a significant change in customer behavior" (Fitch Wire, 2023b). In the case of the Italian life insurer *Eurovita*, the associated capital shortfall led to regulatory interventions and, in particular, the temporary suspension of policyholders' surrender rights (Fitch Wire, 2023a).

Policyholders face relatively low costs of surrender. For example, only 17% of European life insurance reserves carry surrender penalties (EIOPA, 2019), and less than 10% impose surrender penalties of 15% or more (ESRB, 2015). According to anecdotal information from life insurers, surrender penalties in Germany are particularly small (in the range of 2.5% of surrender values) since they are supposed to only cover administrative expenses.

[7] We compute the surrender payouts of German life insurers relative to the sum of premiums and investment income net of insurance benefits and expenses in 2019, using reports by the German Federal Financial Supervisory Authority (BaFin) available at `https://www.bafin.de/DE/PublikationenDaten/Statistiken/Erstversicherung/erstversicherung_artikel.html`.

3 Empirical Analysis

This section provides empirical evidence that higher market interest rates lead to higher life insurance surrender rates.

3.1 Data and Empirical Strategy

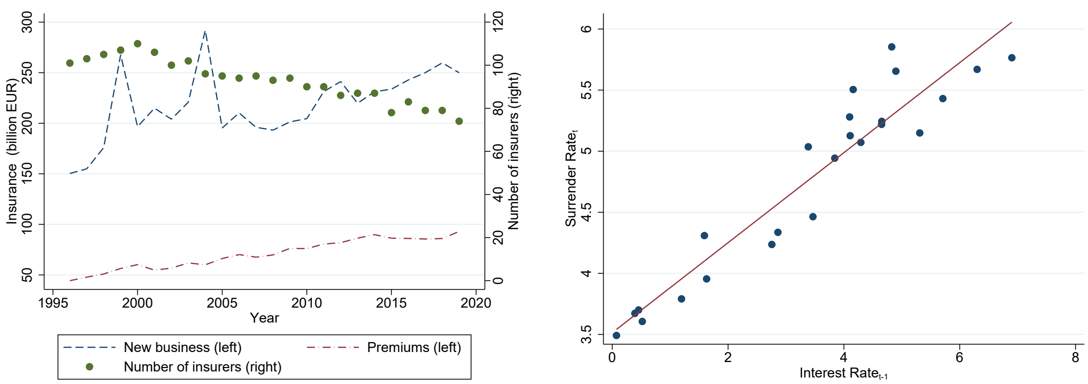
We use the German life insurance market as an empirical laboratory. German life insurers hold more than EUR 1 trillion in life insurance reserves, corresponding to roughly one third of German GDP. Long-term savings contracts with guaranteed surrender values dominate the German life insurance market, as we document in the previous section.

We build our data sample based on the annual insurer-level report *Erstversicherungsstatistik* (i.e., *statistics on primary insurers*) published by BaFin, the German financial supervisory authority. This data set allows us to observe for each German life insurer its surrender rate and volume of insurance business (excluding non-life and reinsurance business). We digitize the data starting in 1995 until 2010, which are available only in print or pdf format. Since a common identifier for insurers is missing in the data, we match insurers by hand over time, resulting in a survivorship-bias-free panel from 1995 to 2019. The panel structure allows us to include insurer fixed effects in regressions, controlling for time-invariant insurer characteristics.

From the Erstversicherungsstatistik, we construct two variables. First, we define an insurer's annual surrender rate as the fraction of life insurance contracts surrendered weighted by the volume of insurance in force. This variable is reported since 2016, while prior to

2016 we construct it from surrender rates separately reported for new and existing business (as described in Internet Appendix C.1). Second, we compute the share of new insurance business (by volume) relative to the previous year-end's existing business.

Figure 1. Sample Characteristics and Visual Inspection of Surrender and Interest Rates. Figure (a) depicts total annual insurance premiums and the volume of new business in billion EUR (left axis) and the number of insurers in each year (right axis) in the sample. New business is measured by volume insured and, thus, exceeds premiums paid. Figure (b) represents a binscatter plot of surrender rates and the 10-year German government bond rate. For each realization of the 10-year German government bond rate, the conditional mean of insurer-level surrender rates is plotted as a scatter point. The figure also includes the line of best fit from a univariate OLS regression.



(a) Sample Size and Dynamics.

(b) Binscatter Plot of Surrender Rates and Interest Rates.

Due to the reconstruction of surrender rates in early years, the final sample starts in 1996. We winsorize insurer-level variables at the 2% and 98% levels to reduce the impact of outliers. The sample comprises 159 life insurers and accounts for EUR 71 billion in insurance premiums in an average year. Aggregate life insurance market dynamics are relatively stable over time (see Figure 1 a). The average surrender rate is 4.8% and varies widely across insurers and years, from 1.7% to 9.6% at the 5th and 95th percentile, respectively, as reported in Table 1.

The main explanatory variable in our regressions is the previous year's market interest rate. We use the annualized yield of German government bonds with a residual maturity of 10 years since it is a widely used benchmark and available with a long history. We lag government bond rates by one year because policyholders may not immediately react to changes in market conditions. The interest rate varies significantly in our sample and ranges from 0.4% to 6.3% at the 5th and 95th percentiles, respectively. The baseline empirical model for an insurer i's surrender rate in year t is

$$\text{Surrender rate}_{i,t} = \alpha \cdot \text{Interest rate}_{t-1} + \beta \cdot \text{New business}_{i,t-1} + \xi \cdot Y_{t-1} + u_i + \varepsilon_{i,t}, \qquad (1)$$

where Interest rate_{t-1} is the 10-year German government bond rate, Y_{t-1} are macroeconomic control variables, and u_i are insurer fixed effects. α estimates the effect of interest rates on surrender rates.[8] Our hypothesis is that higher market interest rates increase surrender rates since they move surrender options toward the money, implying that $\alpha > 0$. We derive this hypothesis in a theoretical model in Section 4.1.2. An increase in market interest rates makes it relatively more attractive to surrender and invest surrender payments in alternative investment products to earn a higher return (e.g., corporate or government bonds) or use them as substitutes for other financing sources, such as mortgages. Consistent with the hypothesis and the specification of the empirical model in Equation (1), the binscatter plot in Figure 1 (b) shows a linear relationship between surrender rates and interest rates.

The Erstversichererstatistik does not provide information at the contract but only at the insurer level, and it constrains the availability of insurer-level control variables. In particular, we do not observe the share of surrenderable contracts, which biases the coefficient

[8]We cluster standard errors at the insurer level to account for time-series dependence of residuals. All results also hold when we additionally cluster at the year level, which we however do not report in the baseline results because the number of clusters may not be sufficient for convergence.

α downwards. We control for variation in contract characteristics and insurance market dynamics by including the lagged share of new business at the insurer level (obtained from the Erstversichererstatistik), New business$_{i,t-1}$, as well as the logarithm of the lagged number of new German life insurance contracts, log(New German contracts$_{t-1}$), and, among these, the share of new term life contracts, New term life$_{t-1}$, as control variables (both made available to us by the German association of insurers (GDV)).

Identifying α in Equation (1) is challenging. Omitted variables might simultaneously affect interest rates and surrender rates. To alleviate this concern, as a first step, we control for the macroeconomic environment by including lagged inflation (retrieved from the BIS), GDP growth and investment growth (retrieved from the OECD), and a banking crisis dummy (from Laeven and Valencia, 2018) as control variables. Table 1 reports summary statistics for these variables, and Table IA.1 in Internet Appendix C.1 details the definitions and sources of all variables in the sample.

Whereas including the control variables improves the identification, there may be other confounders biasing the estimate for α. For example, unobserved changes in government policies could simultaneously affect both interest and surrender rates. Moreover, higher surrender rates may reduce life insurers' bond demand and, thereby, exert upward pressure on bond yields. We tackle these identification challenges in two steps.

First, we dig into the economic mechanism. If policyholders react to interest rate changes due to financial motives, α will decrease with a larger expected contract return (as implied by Equation 5). Because expected contract returns are not observable, in a second empirical specification, we include an interaction term between the interest rate level and the guar-

Table 1. Summary Statistics.
An insurer's surrender rate and share of new business are retrieved from BaFin's *Erstversicherungsstatistik* at the insurer-year level. The sample starts in 1996 and ends in 2019 and includes 159 German life insurers in total. Variable definitions and sources are detailed in Internet Appendix C.1.

	N	Mean	SD	p5	p50	p95
Insurer characteristics (insurer-year level)						
Surrender rate$_{i,t}$ (in ppt)	2,234	4.84	2.40	1.70	4.49	9.55
New business$_{i,t-1}$ (in ppt)	2,234	11.66	8.65	2.21	9.56	30.58
Macroeconomic characteristics (year level)						
Interest rate$_{t-1}$ (in ppt)	24	3.42	1.96	0.39	3.97	6.30
MoPoSurp$_{t-1}$ (in ppt)	24	-3.14	0.90	-4.14	-3.14	-1.71
Guarantee$_{t-1}$ (in ppt)	24	2.60	1.03	0.90	2.50	4.00
New term life$_{t-1}$ (in ppt)	24	21.55	6.09	11.43	20.50	29.60
log(New German contracts$_{t-1}$)	24	14.96	0.37	14.45	15.06	15.61
Inflation$_{t-1}$ (in ppt)	24	1.42	0.59	0.49	1.49	2.28
GDP growth$_{t-1}$ (in ppt)	24	3.60	2.05	1.49	3.67	6.96
Investment growth$_{t-1}$ (in ppt)	24	-0.55	2.96	-5.95	0.13	3.74
Crisis$_{t-1}$ (binary)	24	0.08	0.28	0.00	0.00	1.00

anteed minimum contract return, instead. The guaranteed return is given by the German technical discount rate (Eling and Holder, 2013) and positively relates to expected contract returns. The coefficient on the interaction term reflects whether the sensitivity to the interest rate level changes with a larger guaranteed return. Because the guaranteed return applies only to new contracts, the effect should be stronger for insurers with a larger share of new insurance business. We test this mechanism in a third empirical specification by including a triple interaction term of interest rate, guarantee, and share of new business. Since the estimation of its coefficient relies on variation *across* life insurers, in this specification, we are able to remove unobserved variation in the macroeconomic and financial market environment by including time fixed effects.

Second, we instrument the German government bond rate with U.S. monetary policy surprises. Central bank announcements isolate unexpected variation in monetary policy from economic fundamentals (Gertler and Karadi, 2015; Jarocínski and Karadi, 2020). Because German life insurers' investments in U.S. treasuries are negligible, their bond demand has a negligible impact on U.S. monetary policy.[9] This alleviates potential bias due to reverse

[9]German life insurers held EUR 723.8 million in U.S. treasuries as of 2018 (Source: *EIOPA Insurance*

causality. Even if, despite this reasoning, the exclusion restriction was (partly) violated, the instrumental variable strategy would lead to a more conservative estimate because monetary policy stimulates the economy by *reducing* interest rates in those times, in which deteriorating economic growth might cause increasing surrender rates. Since Equation (1) includes the interest rate in levels, we follow previous literature (e.g., Romer and Romer, 2004) and cumulate monetary policy surprises, using $\text{MoPoSurp}_{t-1} = \sum_{j \leq t-1} m_j$ as an instrument. m_j is the change in fed funds futures from 10 minutes before and 20 minutes after an FOMC announcement on date j, following Jarocínski and Karadi (2020).[10]

3.2 Results

Consistent with the hypothesis that higher interest rates boost surrender rates, the first column of Table 2 documents a positive and highly significant (at the 1% level) coefficient on the German government bond rate in the baseline specification (1). The point estimate implies that surrender rates increase by 25 bps for each 1 ppt increase in the interest rate. A one standard deviation interest rate increase relates to an increase in surrender rates by 0.2 standard deviations (or 48 bps), which in aggregate corresponds to approximately EUR 2.3 billion in surrender payouts.[11] Hence, the magnitude is economically highly significant.

Next, we examine the interaction between interest rates and contracts' guaranteed min-

Statistics), compared to EUR 10,789 billion in publicly held and marketable U.S. government bills, notes, and bonds outstanding in 2018 Q1 (Source: *U.S. Treasury's "Monthly statement of the public debt of the United States"*).

[10] We define m_j as the first principal component of the surprises in interest rate derivatives with maturities from 1 month to 1 year, which we retrieve from Marek Jarocínski's website: `http://marekjarocinski.github.io`.

[11] The annual ratio of aggregate surrender payouts to the aggregate volume of insurance surrendered ranges from 14.1% to 17%, with an average of 15.5% according to BaFin's *Erstversicherungsstatistik* from 2011 to 2019. Using the aggregate volume of insurance in Germany at year-begin 2019 (EUR 3,126 billion), a one-standard-deviation increase in the interest rate approximately corresponds to an increase in surrender payouts of $0.0048 \times 0.155 \times 3,126 \approx$ EUR 2.3 billion.

imum return. Since we only observe the guaranteed return for new insurance contracts, in column (2) we only consider insurers with a large share of new insurance business (i.e., with "young contracts"), namely insurer-year observations with the 50% largest share of new business in the sample. We find a large and significantly negative coefficient on the interaction term between the interest rate and guaranteed returns. This result is consistent with policyholders reacting to surrender options moving toward the money, since a larger guaranteed return implies a lower sensitivity of surrender options to market interest rates.

Because the guaranteed return applies only to new contracts, its effect on surrender rates' interest rate sensitivity should be stronger for insurers with a larger share of new business. We test this hypothesis in the full sample by including a triple-interaction term of interest rates, guaranteed return, and an insurer's share of new business. Importantly, this specification also includes year fixed effects, which remove any unobserved aggregate variation, e.g., in the macroeconomic environment. In column (3), we find that the coefficient on the triple-interaction term is significantly negative. Thus, the negative impact of guaranteed returns on the interest rate sensitivity of surrender rates significantly increases with the share of new business, consistent with the hypothesis.

Columns (4) to (6) provide instrumental variable estimates for the previous specifications. Intuitively, tighter U.S. monetary policy increases U.S. treasury rates, which affect German government bond rates through an international arbitrage channel. Consistent with this intuition, the coefficient on monetary policy surprises is significantly positive in the first-stage regressions. The F statistic in the first stage is well above the critical value of 10, alleviating concerns that the instrument is weak. The IV strategy results in point estimates

Table 2. Surrender Rates and Interest Rates.

This table presents estimates from regressions of insurer-level annual surrender rates on the 10-year German government bond rate from 1996 to 2019. Interest rate$_{t-1}$ is the 10-year German government bond rate. New business$_{i,t-1}$ is the lagged volume of new insurance business relative to that of total insurance business at the previous year's end. Guarantee$_{t-1}$ is the lagged guaranteed minimum return for new German life insurance contracts. Y_{t-1} is a vector of macroeconomic control variables, namely German inflation, GDP growth, investment growth, a banking crisis indicator, the log of the number of new German life insurance contracts and, among these, the share of new term life contracts, all lagged by one year. u_i and v_t are insurer and year fixed effects, respectively. Columns (1) to (3) report OLS estimates. Columns (4) to (6) report IV estimates with lagged cumulative U.S. monetary policy surprises, MoPoSurp$_{t-1}$, as an instrument for the 10-year German government bond rate. The bottom of the table reports first stage results with either Interest rate$_{t-1}$ (columns 4 and 5) or Interest rate$_{t-1}$ · Guarantee$_{t-1}$ · New business$_{i,t-1}$ (column 6) as dependent variable. Detailed variable definitions and data sources are reported in Internet Appendix C.1. t-statistics are shown in brackets, based on standard errors that are clustered at the insurer level. ***, **, * indicate significance at the 1%, 5% and 10% level.

	(1)	(2)	(3)	(4)	(5)	(6)
Dependent variable:	Surrender rate$_{i,t}$					
	OLS			IV		
Sample:	Full	Young contracts	Full		Young contracts	Full
Interest rate$_{t-1}$	0.25***	0.82***		0.23***	1.01***	
	[5.89]	[3.07]		[4.25]	[2.67]	
Interest rate$_{t-1}$ · Guarantee$_{t-1}$		-0.26***			-0.36***	
		[-3.02]			[-3.25]	
Guarantee$_{t-1}$		1.08***			1.53***	
		[4.09]			[4.15]	
Interest rate$_{t-1}$ · Guarantee$_{t-1}$ · New business$_{i,t-1}$			-0.02***			-0.02***
			[-3.56]			[-2.92]
Macro controls	Y	Y		Y	Y	
New business$_{i,t-1}$	Y	Y	Y	Y	Y	Y
Interest rate$_{t-1}$ · New business$_{i,t-1}$			Y			Y
Guarantee$_{t-1}$ · New business$_{i,t-1}$			Y			Y
Insurer FE	Y	Y	Y	Y	Y	Y
Year FE			Y			Y
First stage						
MoPoSurp$_{t-1}$				1.77***	2.19***	
				[205.33]	[28.11]	
MoPoSurp$_{t-1}$ · Guarantee$_{t-1}$ · New business$_{i,t-1}$						0.47***
						[2.66]
F Statistic				6,690	191	212
No. of obs.	2,234	1,111	2,234	2,234	1,111	2,234
No. of insurers	159	135	159	159	135	159
Standardized coefficients						
Interest rate$_{t-1}$	0.20	0.55		0.18	0.68	

and statistical significance of coefficients in the second stage similar to the OLS estimates. These results provide strong evidence for a causal effect of interest rates on surrender rates.

We provide additional results in Table IA.2 in Internet Appendix C.2. First, we address the concern that central bank announcements might also convey information about potentially confounding economic conditions. We follow the methodology in Jarocínski and Karadi (2020) and rely solely on variation from "pure" monetary policy surprises, which are purged of information shocks using stock market reactions. Additionally, we add the ratio of U.S.

imports from Germany relative to all imports and exports between the U.S. and Germany as a control variable for trade links. Nonetheless, the IV estimate for the coefficient on the interest rate hardly changes in magnitude or significance, supporting the initial identification strategy. Second, we show that we also derive a similar estimate when using the 10-year U.S. treasury rate as an alternative instrument, which supports the argument that U.S. monetary policy transmits through an international bond market channel.

Third, we document that the coefficient on U.S. monetary policy surprises becomes insignificant once controlling for the German government bonds rate. This result supports the exclusion restriction: if U.S. monetary policy affected German surrender rates through a channel other than market interest rates, one would expect the coefficient on U.S. monetary policy surprises to remain significant after controlling for German interest rates, contrary to our results.

Finally, we investigate on government bond rate and surrender rate dynamics. Interest rates are on average declining in the sample. To explore whether the effect of interest rates differs between periods with rising and declining interest rates, we estimate the baseline specification in changes, i.e., we regress annual changes in the surrender rate on annual changes in the government bond rate. The coefficient is significantly different from zero and close in magnitude to the coefficient in our baseline model. Thus, common trends in the level of the surrender rate and government bond rate cannot explain the baseline results. In addition, we interact the government bond rate change with a dummy variable that indicates increasing government bond rates. The effect of the interaction term is positive and significant at the 5% level. Thus, the effect of government bond rates on surrender decisions is not weaker but, instead, significantly stronger when interest rates increase.

4 Surrender Options and Financial Fragility

In this section, we develop and calibrate a model that quantifies the impact of surrender options on liquidity in the life insurance sector and spillovers to financial markets.

4.1 Model

We first propose and estimate a model for the surrender of life insurance savings contracts. Second, we embed this model into a broader setting that captures the balance sheet and cash flow dynamics of a representative German life insurer that sells savings contracts with surrender options and minimum guaranteed returns, calibrated to end-of-2015.[12] Below, we describe the defining ingredients of the model and relegate more details to Internet Appendix D, in which we also provide an overview of the model components and their interactions.

4.1.1 Savings Contracts. We model the primary features of German participating life insurance savings contracts, which apply to more than half of the German life insurance market (see Section 2). Specifically, contracts are long term, include a surrender option with guaranteed surrender value, and annually return the maximum of a (at contract origination) fixed guaranteed minimum return and the insurer's investment return. For tractability, we focus on contracts' savings phase and exclude mortality risks. Policyholders annually invest the premium $P > 0$ and receive a lump-sum payout at contract maturity.[13]

[12] A granular stress test by the EIOPA (2016), with January 1, 2016, as the reference date, allows us to calibrate the insurer's balance sheet in great detail. The Fed started to raise interest rates in 2015, while the ECB did not. Assessing the adequacy of rising interest rates after 2015 is beyond the scope of this paper.

[13] Life insurance contracts often allow policyholders to transform the lump sum payout into an annuity at maturity. However, policyholders usually prefer receiving the lump-sum payout, which is referred to as the *annuity puzzle* (see, e.g., Brown, 2001). For instance, more than half of German savings contracts and annuity reserves are for *Kapitalversicherungen* (GDV, 2020), which pay out a policyholder's savings as a

Each year, each policyholder may surrender her contract, upon which the insurer pays out the contract's cash value, which is the contract return accumulated since contract origination less a surrender penalty. Specifically, the total cash value of policyholder cohort h at year-end $t+1$, V^h_{t+1}, evolves after contract origination h, $t+1 > h$, according to

$$V^h_{t+1} = \frac{N^h_{t+1}}{N^h_t} \cdot (1 + \tilde{r}^h_{P,t+1}) \cdot V^h_t + N^h_{t+1} \cdot P^h, \tag{2}$$

where N^h_t is the number of policyholders at year-end t, $\tilde{r}^h_{P,t+1}$ is the contract return credited to policyholders at year-end $t+1$, and P^h are the annual premiums paid by each policyholder to the insurer. Contract returns are given by the maximum of the guaranteed rate of return (determined at contract origination) and the insurer's investment return, as detailed in Internet Appendix D.1.

At contract origination $t = h$, the cash value equals the total premium payments by new policyholders, $V^h_h = N^h_h \cdot P$. We assume that the number of new policyholders at contract origination h is fixed over time, $N^h_h \equiv N$.[14] Policyholder dynamics are driven by the surrender rate λ^h_{t+1}, which is the fraction of the previous year's policyholders that surrender in year $t+1$, $\lambda^h_{t+1} = \frac{N^h_t - N^h_{t+1}}{N^h_t}$. The surrender value of contracts in cohort h, SV^h_t, is determined at year-end t and paid out upon surrender in $t+1$. It equals the lagged cash value V^h_t less the surrender penalty $1-\vartheta$, $\vartheta \in (0,1)$, such that $SV^h_t = \vartheta \cdot V^h_t$.

lump sum at maturity by default.

[14]Time-varying insurance demand is implicitly captured by policyholders' ability to surrender contracts in the first year after purchase. As we show that contract returns react to changes in interest rates with a considerable time lag, it seems likely that life insurance demand decreases following an interest rate rise, reducing the insurer's cash inflow. In this case, the assumption of a fixed number of new policyholders makes our estimates of insurers' asset sales more conservative.

4.1.2 Surrender Decisions.

Motivated by the empirical evidence in Section 3, we model each policyholder's surrender decision as a function of (a) market interest rates, (b) contract return, and (c) contract age.[15]

We consider a policyholder at year-begin t with a contract originated at year-end h, $h < t$. Her current cash value is $v^h_{t-1} = V^h_{t-1}/N^h_{t-1}$, and the surrender value is $sv^h_{t-1} = SV^h_{t-1}/N^h_{t-1}$, both based on year-end $t-1$. While we do not explicitly model fees that cover administrative costs in the insurer's cash flow (since they would net out), fees (and taxes) are a potentially important determinant of surrender decisions. Without loss of generality, we assume that policyholders pay fees at the earlier of the surrender or the maturity date. Cumulative fees (and taxes) are the fraction $1 - e^{-c(t-h-1)}$ of the contract payout, where $c(\cdot)$ is a nonnegative function that increases with contract age $t - (h+1)$.

Surrendering the contract results in additional net utility $e^{\mathcal{L}}$ proportional to the surrender value, which is the utility of satisfying liquidity needs, e.g., arising from medical expenses, net of transaction costs, such as the loss of the option to convert the contract into an annuity or the loss of a death benefit tied to the contract. We allow $\mathcal{L}$ to vary across policyholders, both across and within cohorts, reflecting differences in liquidity needs and transaction costs. The net surrender value is then given by $sv^h_{t-1} \cdot e^{\mathcal{L}-c(t-(h+1))}$.

A policyholder surrenders her contract if the net surrender value exceeds the value of keeping the policy, m^h_{t-1}, net of fees at contract maturity, $1 - e^{-c(T^h-h)}$, i.e., if

$$sv^h_{t-1} \cdot e^{\mathcal{L}-c(t-h-1)} > m^h_{t-1} \cdot e^{-c(T^h-h)}. \tag{3}$$

[15] Bauer et al. (2017) provide a detailed discussion of how to model policyholder behavior in life insurance.

It is straightforward to micro-found this surrender rule with policyholders that compare either keeping the life insurance contract to outside investment opportunities or the surrender option to other funding sources for real investment (such as mortgages) or consumption.

There are three main components that determine the value of keeping the policy: the current market interest rate, expected future contract returns, and the option to surrender in the future. We assume that policyholders approximate expected contract returns by the current contract return, which substantially improves the tractability of the model and is reasonable because investment returns at book value (which determine contract returns) are very persistent (see Section 4.1.4).[16] Moreover, anecdotal evidence suggests that life insurers mainly compete over realized contract returns for new business. Thus, our assumption is plausibly consistent with policyholder behavior. We capture the option value to surrender in the future implicitly in the transaction costs embedded in $\mathcal{L}$ and in the slope of fees $c'(\cdot)$.

Then, m^h_{t-1} is computed using the most recent contract return, $\tilde{r}^h_{P,t-1}$, and German government bond rate with remaining time to maturity $T^h-(t-1)$, $r_{f,t-1,T^h-(t-1)}$, such that

$$m^h_{t-1} = v^h_{t-1}\left(\frac{1+\tilde{r}^h_{P,t-1}}{1+r_{f,t-1,T^h-(t-1)}}\right)^{T^h-(t-1)}. \tag{4}$$

The surrender rule in Equation (3) is equivalent to

$$\mathcal{L} > \log\left[\vartheta^{-1}\left(\frac{1+\tilde{r}^h_{P,t-1}}{1+r_{f,t-1,T^h-(t-1)}}\right)^{T^h-(t-1)}\right] - \Delta c_t. \tag{5}$$

The right-hand side of Equation (5) is the log of the value of keeping the contract relative

[16] In the most extreme case and ignoring depreciations, if the insurer only invested in fixed-coupon bonds with a maturity exceeding that of the contract, contract returns would be constant over time.

to its surrender value, $\log \frac{m^h_{t-1}}{sv^h_{t-1}}$, less future fees $\Delta c_t = c(T^h - h) - c(t - (h+1))$. Thus, lower future fees Δc_t reduce the incentive to surrender (instead, fees for preceding contract years are sunk costs). Marginal fees for life insurance contracts are typically decreasing with contract age, implying that $c(\cdot)$ is concave, $c''(\cdot) < 0$.[17] Δc_t also captures trends in surrender incentives other than fees, which typically give rise to surrender rates that slope down with contract age (Gottlieb and Smetters, 2021; Koijen et al., 2022), such as the value to surrender in the future. We parametrize $c(x) = k \cdot \log(2 + x)$ with $k > 0$ for contract age $x = t - (h+1) \geq 0$.

If $\mathcal{L} = 0$ and $\Delta c_t = 0$, all policyholders surrender if the government bond rate, $r_{f,t-1,T^h-(t-1)}$, exceeds the contract return, $\tilde{r}^h_{P,t-1}$. Heterogeneity in marginal fees across contract age and net surrender utility across policyholders enables us to calibrate the model to empirically observed surrender rates. For this purpose, we assume that $\mathcal{L}$ is normally and independently distributed across policyholders and time with expected value μ_L and variance σ^2_L. Then, the surrender rate in cohort h in year t is given by

$$\lambda^h_t = 1 - \Phi\Bigg(\underbrace{\frac{-k \cdot \log(2 + T^h - h) - \mu_L}{\sigma_L}}_{=\beta_0} + \underbrace{\frac{1}{\sigma_L}}_{=\beta_1} \cdot \log \frac{m^h_{t-1}}{sv^h_{t-1}} + \underbrace{\frac{k}{\sigma_L}}_{=\beta_2} \cdot \log(2 + (t - (h+1)))\Bigg), \tag{6}$$

which, ceteris paribus, increases with the government bond rate. $\Phi(\cdot)$ is the cumulative distribution function of the standard normal distribution.

Estimating β_0, β_1, and β_2 requires knowledge about the cross-section of surrender rates by contract age and return. Since such data is not available over time, we estimate β_0, β_1, and β_2 by matching the surrender rate in the Erstversicherungsstatistik to the cross-sectional

[17] For example, German life insurers must deduct fees evenly distributed across a contract's first 5 years (§169 Insurance Contract Act).

distribution of surrender rates implied by our model at $t = 1$, as described in Internet Appendix D.2. As one would expect, the estimated surrender rate slopes down with the contract return since a higher contract return increases the opportunity cost of surrender. Instead, when the contract return approaches zero, the surrender rate approximately equals 15% to 20%, which is close to the stress scenario estimated by Biagini et al. (2021).

4.1.3 Balance Sheet and Portfolio Allocation.

We track the insurer's balance sheet at both mark-to-market (consistent with regulation) and book value (consistent with national GAAP) accounting. The insurer's contract portfolio consists of several cohorts. Contracts have a fixed lifetime of $T^h - h = 40$ years at contract origination and differ according to their age. The starting point of the model is the end of year $t = 0$, which we calibrate to end-of-2015. The contract portfolio consists of 40 cohorts. The oldest cohort $h = -39$ was sold at year-end $t = -39$ (i.e., 1976) with guaranteed return $r_G^{-39} = 3\%$, and the latest was sold in $t = 0$ (i.e., 2015) with $r_G^0 = 1.25\%$, as implied by the historical evolution of guaranteed returns in Germany.

Table 3. Initial Calibration of the Insurer's Balance Sheet.

Variable	**Initial value**
Average surrender rate	3.26%
Average guaranteed return	3.12%
Avg. remaining contract lifetime	25.60
Equity capital / assets	9.00%
Modified Duration (Contracts)	14.10
Modified Duration (Assets)	9.31

To compute the relative size of cohorts at $t = 0$, we draw on the historical evolution of the volume of new life insurance, average surrender rates, and contract returns in Germany and extrapolate where needed, as described in Internet Appendix D.4. The resulting initial contract portfolio exhibits an average guaranteed return of 3.12% per contract (see Table 3), similar to the one observed in 2015 (Assekurata, 2016). The modified duration of the initial contract portfolio is 14.1 years, which coincides with the median duration of German life insurers' liabilities according to the German association of insurers (GDV).

The insurer invests in government bonds, corporate bonds, stocks, and real estate. The detailed modeling of the insurer's fixed-income portfolio is important to calibrate the investment return dynamics, which determine contract returns and cash flows. The relative weights and interest rate durations of asset classes are calibrated based on (GDV, 2016) and (EIOPA, 2014, 2016), as detailed in Internet Appendix D.5. Fixed income is the most important asset class, with 55% of assets invested in government bonds and 34% invested in corporate bonds.

Given the investment portfolio, the contract portfolio, and asset prices (as implied by the financial market model described in the next section) at year-end $t = 0$, we determine the insurer's leverage by matching the ratio of equity capital to total assets (both at market value) of 9%. This level corresponds to the ratio of equity capital to total assets of 8.8% for the average German life insurer in January 2016 (EIOPA, 2016).[18] It is also consistent with the ratio of market equity to total assets of listed European life insurers in 2015.[19] The resulting initial calibration, as reported in Table 3, closely matches the balance sheet of German life insurers in 2015. Supporting the calibration of the insurer's investment portfolio,

[18]Specifically, EIOPA (2016, Figure 10) reports that total assets divided by total liabilities is 109.5% for a large sample of German insurers that consists almost entirely of life insurers. This corresponds to a capital ratio of 8.8%. We compute life insurance liabilities as outlined in Internet Appendix D.3.

[19]We retrieve quarterly data on market capitalization and total assets for all firms classified by Thomson Reuters Eikon as European life insurers and then take the average ratio of market capitalization to total assets across quarters in 2015 for each firm. The ratio of market capitalization to total assets ranges from 2.4% to 13.7% at the 10th and 90th percentile, respectively.

our model predicts an average investment return of 3.45% for 2016 ($t = 1$), which closely resembles the investment return of the median German life insurer in 2016 (3.04% as reported in BaFin's Erstversicherungsstatistik).

Starting with the initial investment portfolio, we explore two possible investment strategies. First, in the baseline results, we provide a benchmark by assuming that the insurer keeps the relative portfolio weights fixed at market values. This investment strategy maintains a similar level of investment risk over time and ensures that the results are not driven by changes in the investment portfolio. Second, we implement a dynamic duration matching strategy. In this case, the insurer targets a constant relative duration gap, which is

$$\frac{D_0^L - D_0^A}{D_0^L} = \tilde{D}, \tag{7}$$

where D_0^A is the initial asset duration, D_0^L is the initial liability duration, and $0 < \tilde{D} < 1$ is the target relative duration gap. This assumption is broadly consistent with Ozdagli and Wang (2020)'s model, in which $\tilde{D}$ equals one minus the insurer's leverage ratio. As observed in practice, $D_0^L > D_0^A$. Based on the new duration of liabilities D_t^L at year-end t, the insurer adjusts the duration of the investment portfolio to maintain the duration gap $\tilde{D}$. For this purpose, portfolio weights are redetermined such that the duration within each asset class matches its initial duration multiplied by the scaling factor $(1 - \tilde{D}) \cdot D_t^L / D_0^A$ (as described in Internet Appendix D.5).

4.1.4 Financial Market Model. We use a stochastic financial market model to simulate German government bond rates, (2) bond spreads, and (3) stock and real estate returns.

Short rates evolve according to Vasicek (1977)'s model and drive the evolution of German government bond rates, calibrated as described in Internet Appendix D.6. Bond spreads follow Ornstein-Uhlenbeck processes, and stocks and real estate indices follow geometric Brownian motions. All models are calibrated based on monthly data from December 2000 to November 2015, as described in Internet Appendix D.7.

4.1.5 Asset Sales and Price Impact. At the end of each year t, (1) the insurer pays out surrender values, (2) investment returns realize, (3) contract returns are credited to non-surrendered contracts, (4) active (non-surrendered and non-matured) policyholders pay premiums, and (5) a new contract cohort is created (as illustrated in Figure IA.2 in Internet Appendix D). These dynamics determine the insurer's free cash flow, which is the difference between cash inflow (the sum of premiums paid, investment income, and bond redemptions) and cash outflow (the sum of payouts for matured and surrendered contracts). Given the free cash flow, the insurer purchases or sells assets to match the target portfolio weights.

Motivated by prior literature (Ellul et al., 2011; Girardi et al., 2021; Liu et al., 2021; Ellul et al., 2022) and the importance of asset sales for financial stability, we focus on the asset price impact of insurers' asset sales.[20] We distinguish between (1) short-term bonds (those with a remaining time to maturity of up to 10 years), (2) long-term bonds (those with a remaining time to maturity of more than 10 years), and (3) stocks and real estate. Then, the market value of the insurer's total (invested) assets at year-end t after realization of cash

[20] Accounting for the price impact of asset purchases would have negligible effects on our results since we focus on scenarios in which the insurer's free cash flow becomes negative and, thus, asset purchases are quantitatively negligible.

flows and readjustment of the insurer's investment portfolio (i.e., time $t+$) is

$$A_{t+} = A_{t-} + FCF_t - FSC_t, \tag{8}$$

where A_{t-} is the market value of total assets at year-end t before cash flows realize, FCF_t is the free cash flow, and FSC_t are fire sale costs resulting from the insurer's price impact. w_t^k is the target weight for asset class $k \in \mathcal{K} = \{\text{short-term bonds}, \text{long-term bonds}, \text{stocks \& real estate}\}$ at time $t+$, and by a_{t-}^k the market value of assets in class k at time $t-$. Net sales in asset class k (based on prices at $t-$) are thus equal to $-(w_t^k A_{t+} - a_{t-}^k)$.

Following Greenwood et al. (2015), we assume that $\delta = 10^{-4}$ (1 bps) is the price impact per EUR 1 billion of net sales within each asset class. Whereas this assumption is simplistic, it minimizes the number of parameters that must be calibrated, and it is very transparent. Nonetheless, it is straightforward to implement other price impact functions. The calibration of δ is consistent with the price impact of U.S. insurers' fire sales after bond downgrades (Ellul et al., 2011). We assume that the price impact dissolves within 1 year, which is in line with empirical evidence that prices typically revert within 6 to 8 months (Ellul et al., 2011; Kubitza, 2023; Massa and Zhang, 2021).

To compute meaningful estimates for the insurer's price impact, we need to specify the size of its balance sheet. Interest rate changes systematically affect surrender incentives of contracts with similar contractual features. To account for this systematic effect, we scale our model by the factor Ω such that the total volume of life insurance reserves in the model equals that of European participating life insurance contracts with surrender guarantees, which we estimate to be 80% of European life insurance reserves for participating contracts in 2016Q3 ($0.8 \cdot$ EUR 5.238 trillion).[21] The scaling factor is conservative because insurers also offer surrender guarantees on nonparticipating contracts (EIOPA, 2019), which we exclude because of their different investment dynamics.

Under these assumptions, the total fire sale costs in asset class k are given by

$$\underbrace{\delta \cdot \Omega \cdot \max\{-(w_t^k A_{t+} - a_{t-}^k), 0\}}_{\text{Price impact}_t^k} \cdot \underbrace{\max\{-(w_t^k A_{t+} - a_{t-}^k), 0\}}_{\text{Sales}_t^k}. \tag{9}$$

The price impact reflects externalities generated by asset sales on other institutions. Plugging this expression into Equation (8) yields

$$A_{t+} = A_{t-} + FCF_t - \sum_{k \in \mathcal{K}} \delta \cdot \Omega \cdot \max\{-(w_t^k A_{t+} - a_{t-}^k), 0\}^2. \tag{10}$$

The insurer's previous year's asset allocation, contract portfolio, and the financial market model jointly determine A_{t-}, a_{t-}^k, and FCF_t. The investment strategy determines w_t^k (which is either fixed or varying with the duration of liabilities). δ and Ω are exogenous parameters. Given these variables, we use Equation (10) to determine the market value of total assets A_{t+}, which then determines fire sale costs and the asset allocation.[22]

Our approach to computing insurers' asset sales and price impact makes two important assumptions. First, insurers do not finance surrender payouts with financial debt. This assumption is consistent with the observation that life insurers' debt liabilities are small in

[21] Source: *EIOPA Insurance Statistics*. German life insurance reserves account for approximately 19% of European life insurance reserves. Whereas our model is calibrated based on data from 2015, the earliest available data on European life insurance reserves under a uniform accounting regime (following the Solvency II standards) are from 2016Q3. Since the volatility of European life insurance reserves over time is very low (the standard deviation of quarterly European life insurance reserves between 2016Q3 and 2018Q1 is approximately 2% relative to 2016Q3), we use the value from 2016Q3 to scale our model.

[22] We numerically solve Equation (10), selecting the solution with minimal fire sale costs.

practice, especially compared to surrender payouts. For example, surrender payouts correspond to more than six times the volume of insurers' financial liabilities to credit institutions (Source: *EIOPA Insurance Statistics*). Moreover, borrowing costs likely exceed fire sale costs (the latter do not exceed 70 bps in our baseline results), especially during an interest rate rise, and increased borrowing may be perceived as a negative signal about an insurer's liquidity.

Second, we assume that policyholders do not immediately reinvest surrender payouts in the same assets that insurers sell.[23] Instead, there may be a significant time lag between surrender and re-investment, policyholders may invest in different assets (e.g., because of different risk preferences), or consume (e.g., by using the surrender payout as an alternative to loans). For example, we document a positive correlation between surrender payouts and private consumption in Germany in Internet Appendix E. Since the price impact in Equation (9) is linear in the volume of sales, it is, however, straightforward to relax this second assumption: if policyholders immediately reinvested $x\%$ of surrender payouts in the same assets that insurers sell, the price impact would be $x\%$ smaller.

4.2 Baseline Results

We simulate 80,000 paths of the financial market model with a length of 10 years in Matlab. The dynamics of simulated interest rates and stock prices closely resemble those historically observed (as illustrated in Figure IA.5 in Internet Appendix D.7). To assess the risk posed by surrender options in an environment with rising interest rates, among all simulated paths we focus on the 5% with the largest average increase in the 10-year German government bond

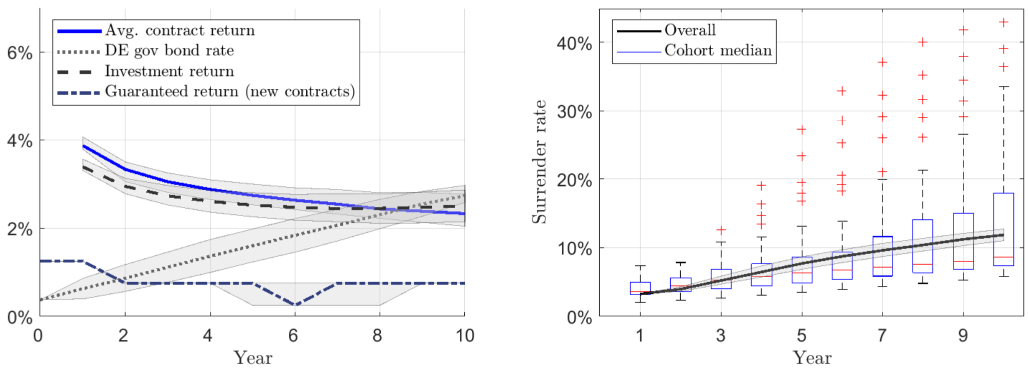
[23] Note that, upon an interest rate rise, insurers' depreciated long-term investments restrict them from offering new contracts with higher returns to existing policyholders.

rate. Among these paths with rising rates, on average, interest rates increase annually by 25 bps. This pace is plausible compared to the historical evolution of bond rates and matches the 75th percentile of annual changes in the 10-year German government bond rate since 1980. We describe the results focusing on the median outcome across the interest rate rise paths. In addition, we report the 25th and 75th percentiles, which illustrate the variation in outcomes implied by the calibrated variation of interest rates and surrender decisions.

4.2.1 Slow Pass-Through of Interest Rate Changes. Figure 2 (a) depicts the dynamics of market interest rates, the insurer's investment return and contract returns. The investment return is based on book values, which is the relevant metric to determine contract returns (see Equation IA.2 in Internet Appendix D.1). Although the simulated 10-year German government bond rate increases over time, the insurer's investment return decreases. The reason for this divergence is the long duration of the insurer's investments, which implies that the historical decline in interest rates dominates the investment return dynamics. Old long-term bonds with high yields are gradually replaced by new bonds with relatively lower (yet increasing) yields. Given the initial asset duration of 9.3 years, it takes approximately the same time until the insurer's investment return begins to rise. Thus, there is a slow pass-through of an interest rate rise to the insurer's investment return.

Figure 2 (a) also shows that contract returns closely follow the insurer's investment return and, therefore, the slow pass-through to the investment return translates into a slow pass-through to contract returns. The co-movement of investment and contract returns is intuitive since, during an interest rate rise, existing contracts have relatively low guaranteed returns (implied by initially low interest rates), which, thus, are often not binding. Whereas

Figure 2. Interest Rate, Contract Return, and Surrender Rate.
Figure (a) depicts the simulated contract return for an average cohort, 10-year German government bond rate, the insurer's investment return, and the guaranteed return for new contracts (median and 25th / 75th percentiles). The investment return is computed as the ratio of investment income without considering depreciations relative to the insurer's lagged book value of assets. Figure (b) depicts the share of surrendered contracts (straight lines; median and 25th / 75th percentiles) and the distribution of each cohort's median surrender rate across cohorts (boxes; defined by the 25th, 50th, and 75th percentiles).



(a) Interest Rate and Returns. (b) Surrender Rate.

the figure depicts the investment return at book value before accounting for asset depreciations (which occur when market values fall below historical cost values), contract returns follow the investment return *after* depreciations (see Equation IA.2 in Internet Appendix D.1). Depreciations may thus reduce contract returns below the investment return (before depreciations), as in years $t = 9$ and $t = 10$ in Figure 2 (a).

Due to these return dynamics, the difference between contract returns and the market interest rate shrinks. As a result, policyholders' incentives to surrender strengthen. In the simulations, the average surrender rate increases from approximately 3.3% at model begin to nearly 12% after 10 years of rising interest rates (see Figure 2 b).[24] A surrender rate of 12% corresponds to the 97th percentile of German life insurers' surrender rates from 1996 to 2019.

[24]Note that the correlation between surrender rates and interest rates is larger in the simulations than in the empirical analysis in Section 3. The reason is that the model starts at a particularly low level of interest rates after a long period of declining interest rates, which implies that low contract returns and low guarantees amplify the interest rate sensitivity of surrender rates (see Equation 5). Supporting this explanation, in additional regressions with the sample from Section 3, we find that *Interest rates*$^2_{t-1}$ enters with a significantly negative coefficient, which implies that a lower interest rate associates with a larger interest rate sensitivity.

It is substantially below a surrender rate of 20-25%, which according to Biagini et al. (2021) would constitute a "mass cancellation scenario", and below 40%, which is assumed to reflect a mass cancellation scenario in European insurance regulation. Figure 2 (b) shows that surrender rates increase for the average cohort with wide variation across cohorts. Younger cohorts with a long remaining time to maturity are more sensitive to an increase in interest rates than older cohorts and, thus, drive the increase in surrender rates.

4.2.2 Interest Rate Convexity. The increase in surrender rates reduces the interest rate duration of individual insurance contracts when interest rates rise. Thus, surrender options contribute to life insurance convexity. This effect on the contract portfolio's duration is amplified by cross-sectional heterogeneity in surrender rates: younger cohorts are more interest rate sensitive, and thus, their particularly high surrender rates reduce their weight within the insurer's contract portfolio. As a consequence, older cohorts with a shorter duration gain higher weight and further reduce the *average* duration in the contract portfolio. In addition to this downward pressure on the contract portfolio duration, differences in cohort size and guaranteed returns affect duration dynamics. Older cohorts have higher guaranteed returns, and thus, their cash value grows faster than that of younger cohorts, amplifying the decline in contract portfolio duration. These effects interact with size differences across cohorts and can mitigate or further boost the decline in duration.

To disentangle the impact of interest-rate-driven surrenders from baseline effects, we compare our results to a counterfactual calibration in which the surrender rate is held constant at the initial surrender rate level for each policyholder. We interpret this counterfactual calibration as an environment in which policyholders surrender exclusively due to idiosyncratic liquidity needs. In this case, the duration of contracts is decreasing due to baseline and portfolio effects, as the contract portfolio shifts from younger contracts with longer duration to older contracts with shorter duration. The average modified duration of the contract portfolio declines from 14.1 years at $t = 0$ to 8.7 years at $t = 10$.

In our baseline calibration, the interest rate sensitivity of surrender rates amplifies the decline in contract duration. In this case, the modified duration declines to 6.5 years at $t = 10$. The difference from the counterfactual calibration with a constant surrender rate combines two effects: (1) reallocation of cash flows *within* contracts, as higher surrender rates reduce contracts' expected lifetime, and (2) changing portfolio composition, as younger contracts are relatively more interest rate sensitive and, thus, have higher surrender rates, increasing the relative size of older contracts.

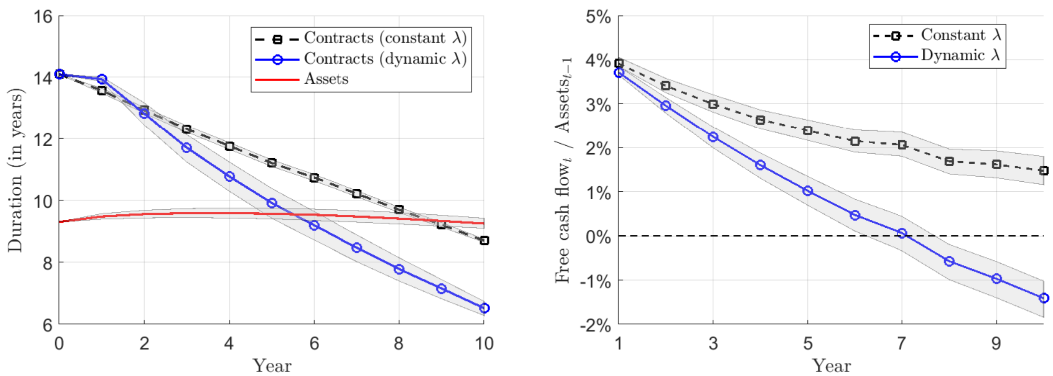
As a result, the overall duration of the contract portfolio declines by an additional 2 years (or, equivalently, 25%) and even strongly below the duration of the insurer's investments. Hence, a gradual but long-lasting interest rate rise can reverse life insurers' duration gap: although the duration gap is initially negative (i.e., contracts have a longer duration than asset investments), it becomes positive after 6 years.

4.2.3 Free Cash Flow and Asset Sales.

High surrender rates translate into large surrender payouts to policyholders. These payouts negatively affect the insurer's free cash flow, as Figure 3 (b) shows. In the counterfactual calibration with constant surrender rates, the free cash flow remains positive, i.e., total inflows exceed payouts for matured and surrendered contracts. Instead, in the baseline calibration, large surrender rates drive the free cash flow into negative territory starting after year $t = 7$. The longer the interest rate rise lasts, the larger is the total annual net outflow, which reaches nearly 1.5% of total assets after 10 years.

Figure 3. Duration and Free Cash Flow.

Figure (a) depicts the modified duration of the insurer's fixed-income investment portfolio (solid line), of the insurer's contract portfolio in the case of a constant (exogenous) surrender rate λ (squares), and of the insurer's contract portfolio in the case that the surrender rate λ is endogenously determined depending on the market environment (circles). Asset duration dynamics do not differ across calibrations with constant or dynamic surrender rates. Figure (b) depicts the insurer's free cash flow before accounting for fire sale costs relative to lagged total assets. We show the median and 25th / 75th percentiles in each year.



(a) Duration. (b) Free Cash Flow.

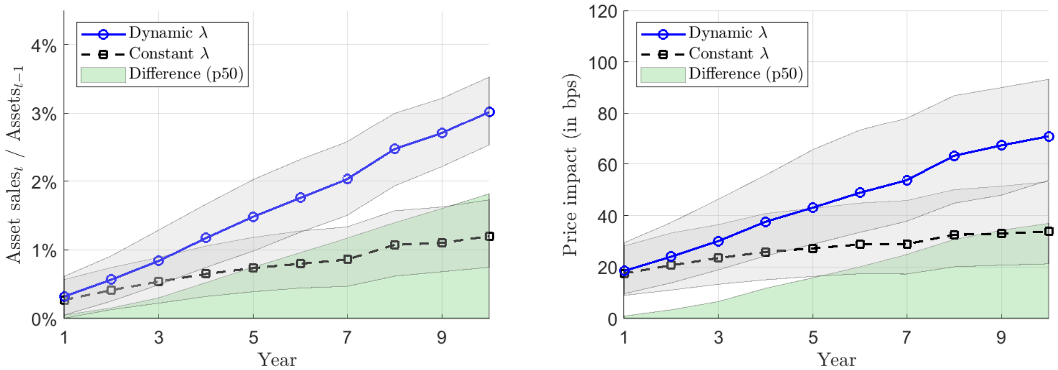
As a result, the insurer is forced to sell assets. We compute the volume of asset sales as the sum of net sales within asset classes, $\text{Sales}_t = \sum_{k\in\mathcal{K}} \max\{-(w_t^k A_{t+} - a_{t-}^k), 0\}$. Market segmentation implies that purchases in one asset class cannot offset the price impact in another asset class. Therefore, Sales_t may exceed the insurer's net outflow. In the simulation, the volume of asset sales corresponds to up to 3% of total assets after 10 years of rising interest rates (see Figure 4 a). Thus, portfolio rebalancing increases the volume of asset sales by approximately 1.5% of total assets, relative to that implied by net cash outflows.[25]

To assess the price impact of asset sales, we compute the volume-weighted average price impact, $\sum_{k\in\mathcal{K}} \text{Price impact}_t^k \cdot \text{Sales}_t^k / \sum_{k\in\mathcal{K}} \text{Sales}_t^k$ (following the definitions in Equation 9),

[25]Note that the level of Sales_t depends on the level of market segmentation. The more segmented the market, the larger is the sum of segment-level net sales. By assuming segmentation of the bond market into only two segments, our results are conservative relative to the actual segmentation of markets in practice. Kubitza (2023) provides empirical evidence for more granular segmentation at the bond issuer level.

Figure 4. Asset Sales and Price Impact.

The figures depict (a) the insurer's asset sales relative to previous year's total assets and (b) their average price impact. The average price impact is calculated as the price impact per EUR 1 sold, defined as the average asset class-specific price impact (see Equation 9) weighted by the asset class-specific volume of sales. Both figures depict the median and 25th/75th percentile for each year for the baseline calibration, under which the surrender rate λ is endogenously determined depending on the market environment (circles), and for a counterfactual calibration, under which λ is constant over time (squares), as well as the difference between the respective median values (green area).



(a) Asset Sales. (b) Price Impact.

which reflects the average price impact per EUR 1 sold. In the simulations, the insurer's asset sales depress prices by up to 71 bps (see Figure 4 b). The magnitude of this price impact is economically significant. For example, Massa and Zhang (2021) document that nonfinancial firms reacted to corporate bond price declines of approximately 50 bps by adjusting their debt structure after hurricane Katrina forced insurance companies to sell bonds. Importantly, the annual volume of asset sales and, thus, the price impact increases with the length of the interest rate rise. The reasons are that an enduring interest rate rise (1) increases the wedge between insurer's investment return and market interest rates (see Figure 2), amplifying surrender incentives, and (2) depresses the prices of long-term relative to short-term bonds, resulting in portfolio rebalancing (see below).

To what extent are asset sales driven by the interest rate sensitivity of surrender options? To answer this question, Figure 4 compares asset sales and the price impact in the baseline calibration to those in the counterfactual calibration with a constant surrender rate. In this counterfactual calibration, sales are driven exclusively by portfolio rebalancing since the free cash flow remains positive, i.e., surrenders do not force the insurer to sell assets (see Figure 3). The difference between this counterfactual calibration and the baseline results reflects the impact of interest-rate-driven surrenders. These *surrender-driven* asset sales amount to nearly 2% of the insurer's assets and depress prices by nearly 40 bps at $t = 10$. Thus, the interest rate sensitivity of surrender options accounts for the majority of asset sales (60%) and their price impact (52%).

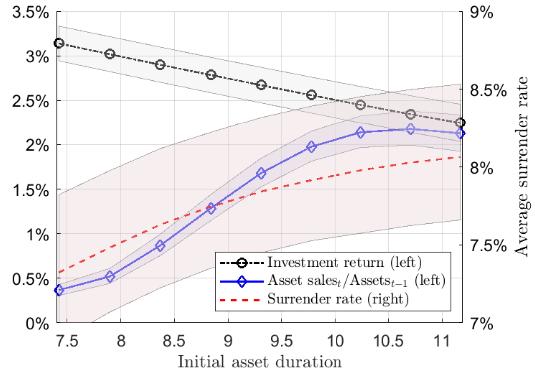
4.3 Counterfactual Calibration: Role of Long-Term Investments

An interest rate rise bolsters surrender incentives because of its slow pass-through to contract returns. Intuitively, a long duration of the insurer's fixed-income investments isolates coupon payments from fluctuations in the interest rate. Thereby, a long duration prevents contract returns from catching up with higher interest rates, which incentivizes policyholders to withdraw their ex ante guaranteed surrender value. We explore this mechanism by using counterfactual calibrations of our model. Specifically, we vary the duration of the insurer's fixed-income investment portfolio by re-scaling the duration of government bond investments, and then re-simulate the model (with the same insurance contract portfolio as in the baseline calibration). We consider an initial duration of the fixed-income portfolio between 7.4 and 11.2 years, which is in the upper half of the cross-country distribution of European insurers (EIOPA, 2016).

Consistent with the described mechanism, Figure 5 shows that a longer duration of

Figure 5. Counterfactual Calibration: Role of Long-Term Investments.

The figure depicts the insurer's investment return (left axis), ratio of asset sales to lagged total assets (left axis), and surrender rate (right axis), all for an average year and with the median and the 25th/75th percentiles across simulations. We vary the initial duration of the insurer's government bond portfolio (holding the ratio of durations across different types of government bonds constant), and denote the resulting initial duration of fixed-income investments on the x-axis.



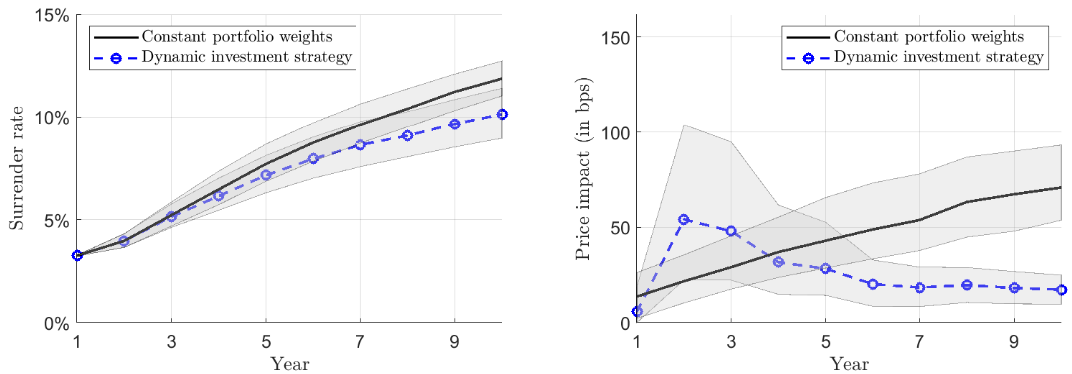
the insurer's investments leads to a lower investment return during an interest rate rise. Specifically, the investment return in an average year is approximately 90 bps (29%) smaller when the investment duration is 3.8 years longer, namely, 11.2 instead of 7.4 years. As a result, surrender incentives strengthen: the surrender rate in an average year is approximately 70 bps (10%) higher in case of a longer duration.

This increase in surrenders forces the insurer to sell more assets. The share of assets sold in an average year is more than 5 times larger (namely, 2.1% instead of 0.4%) when the investment duration increases by 3.8 years. Consequently, the insurer's price impact is also larger, as it increases from 14 bps to 58 bps in an average year. Thus, long-term investments are a crucial driver of asset sales and price impact during an interest rate rise.

4.4 Counterfactual Calibration: Role of Investment Strategies

In the baseline calibration, the insurer keeps investment portfolio weights constant over time. However, when the contract duration declines as a result of rising interest rates (see Figure 3), insurers are inclined to reduce their asset duration (Domanski et al., 2015; Ozdagli and Wang, 2020). We implement such a dynamic investment strategy in a counterfactual calibration, assuming that the insurer targets a constant relative duration gap between fixed-income investments and contracts.

Figure 6. Counterfactual Calibration: Surrender Rate and Price Impact with Dynamic Investment Strategy.
Figure (a) compares the insurer's surrender rate in the baseline calibration with constant portfolio weights to that in a counterfactual calibration with a dynamic investment strategy. Figure (b) compares the insurer's price impact in the baseline calibration with constant portfolio weights to that in a counterfactual calibration with a dynamic investment strategy. Both figures show the median and 25th/75th percentile for each year.



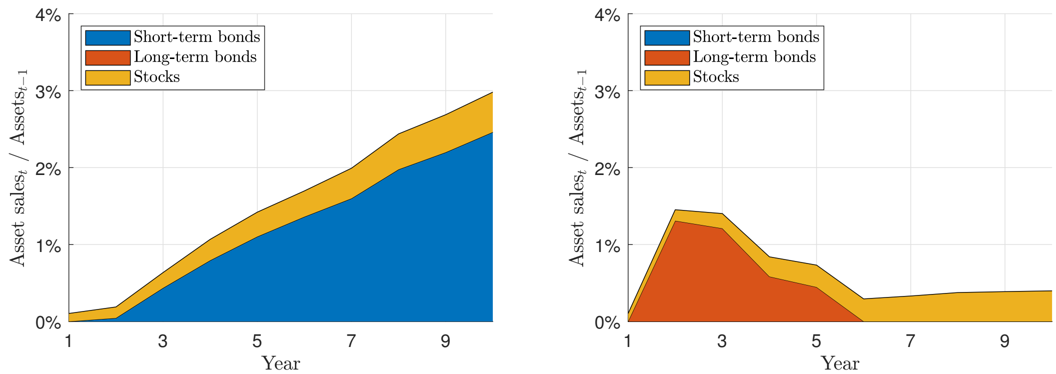
(a) Surrender Rate. (b) Price Impact.

Figure 6 (a) depicts the asset sales and price impact if the insurer implements the dynamic investment strategy. We find that the peak price impact, 54 bps, is slightly smaller than that with constant portfolio weights. Moreover, the timing substantially differs. Whereas asset sales increase over time with constant portfolio weights, with a dynamic investment strategy, asset sales realize primarily in the early years of an interest rate rise. After approximately 5 years, asset sales and the price impact stabilize at low levels.

Hence, the dynamic investment strategy prevents the insurer from being *forced* to sell assets in late years by (partly) substituting short-term for long-term bonds in early years. This substitution in early years strengthens the pass-through of interest rates, which reduces

Figure 7. Counterfactual Calibration: Asset Sales across Asset Classes.

The figures depict the median ratio of asset sales to previous year's total assets for each year and asset class, where short-term bonds are those with a maturity of up to 10 years and long-term bonds are those with a maturity larger than 10 years. Figure (a) is based on the baseline calibration in which the insurer keeps the asset portfolio weights constant. Figure (b) is based on a counterfactual calibration in which the relative duration gap is kept constant.



(a) Constant Portfolio Weights.

(b) Dynamic Investment Strategy.

surrender rates (see Figure 6 b). Figure 7 illustrates the allocation of asset sales. It compares the asset sales by asset class under a dynamic investment strategy with those under constant portfolio weights. In addition to the difference in timing, there is a substantial difference in the assets being sold. If the insurer follows a dynamic investment strategy, it sells almost exclusively long-term bonds to reduce the asset duration, matching the declining duration of insurance contracts. Instead, if the insurer targets constant portfolio weights, it sells almost exclusively short-term bonds. The reason is that the prices of longer-term bonds decline relative to that of shorter-term bonds when interest rates increase. To counteract this shift in relative prices and to maintain constant portfolio weights, the insurer sells short-term rather than long-term bonds.

4.5 Counterfactual Calibration: Market Value Adjustments

An important driver for interest-rate-driven surrenders is that the surrender value is guaranteed ex ante, i.e., independent of short-term fluctuations in interest rates. Market value adjustments (MVAs) adjust surrender values for interest rate changes: an increase in interest rates reduces market-value-adjusted surrender values, everything else being equal.

As detailed in Internet Appendix F.1, we implement a MVA typically found in the U.S. in our model. The MVA reduces the surrender rate, which translates into a lower volume of asset sales and lower price impact. The peak price impact is roughly 25% lower, namely 53 bps with MVA rather than 71 bps in the baseline calibration. Thus, a MVA can significantly reduce the price pressure resulting from interest-rate-driven surrenders.

5 Empirical Predictions and Policy Implications

Our analysis sheds light on the interaction between interest rates, surrender options, and liquidity risk in life insurance. Thereby, it makes several empirical predictions.

First, we uncover substantial interest rate convexity in life insurance savings contracts. In our baseline calibration, surrender options depress the duration of life insurance contracts by approximately 2 years during an interest rate rise of 25 bps per year. This *convexity* is consistent with empirical evidence on the interest rate sensitivity of life insurers' equity prices. For example, Hartley et al. (2017) and Ozdagli and Wang (2020) document that U.S. life insurers' equity prices are relatively less interest rate sensitive when interest rates are higher, consistent with a then lower duration of life insurance contracts and, thus, lower duration gap. Life insurance convexity implies that it can be optimal for life insurers to maintain a negative duration gap to reduce their exposure to an interest rate rise, a characteristic of life insurers observed in many markets.[26]

Second, convexity incentivizes insurers to reduce the duration of their investments during an interest rate rise to match changes in contract duration (Ozdagli and Wang, 2020). A collective rebalancing can induce upward pressure on long-term relative to short-term yields, analogous to the effect of prepayment options for fixed-rate mortgages (Hanson, 2014). This prediction is consistent with the results in Domanski et al. (2015), who document that German life insurers increase their investments' duration when interest rates decline and that the resulting demand for long-term bonds further reduces long-term yields.

Third, our results suggest that surrender options can force life insurers to liquidate a substantial share of their assets. In our baseline calibration, we estimate an asset price impact of surrender-driven asset sales of 40 bps after 10 years of rising interest rates. This result predicts that the prices of bonds held by those life insurers that offer surrender guarantees depreciate more during an interest rate rise than those of other bonds. The surrender-driven pressure to sell assets may add to other sources of life insurers' liquidity demand, such as the obligation to post variation margins for interest rate swaps (De Jong et al., 2019).

Because asset sales can amplify market instabilities, an important question is how to mitigate interest rate sensitivity of surrender rates. The primary reason for interest rate sensitivity is that surrender values do not adjust to interest rates in the short run. Therefore, allowing surrender values to fluctuate with asset prices can reduce the interest rate sensitivity

[26]Note that negative duration gaps, however, increase insurers' exposure to an interest rate decline. Thus, the appropriate duration gap significantly depends on an insurer's expectations about future interest rate changes.

of surrenders. MVAs adjust surrender values to interest rate changes by comparing the current and past levels of interest rates. We implement such an MVA in our model and show that it can substantially reduce surrender-driven asset sales during an interest rate rise. Therefore, MVAs can be a viable policy tool to mitigate collective asset sales.[27]

Policymakers have suggested the use of surrender penalties and payout limits to mitigate surrender-driven risks to life insurers' liquidity and financial stability (e.g., EIOPA, 2020).[28] In contrast to MVAs, surrender penalties reduce the *average* level of surrender rates. Thus, such penalties are also costly for policyholders when there is no risk of forced asset sales. Whereas a limit to surrender payouts can reduce asset sales resulting from fundamentals-driven surrenders, it would also strengthen strategic complementarities in the actions of policyholders giving rise to non-fundamental surrender incentives. Moreover, limiting surrender payouts can impose significant costs on policyholders with high liquidity needs. For these reasons, MVAs may be a more effective tool to mitigate surrender-driven asset sales. Nonetheless, since MVAs also impose costs on policyholders by reducing the possibility to hedge tight financial conditions, it is important to investigate the potential costs of these policies from households' perspective in future work.

6 Conclusion

Surrender options allow life insurance policyholders to terminate their contracts before maturity and receive an ex ante guaranteed surrender value. When interest rates rise, this

[27]MVAs are common in U.S. deferred annuities, but not in most European life insurance markets. A potential explanation is that it is individually optimal for European life insurers not to offer MVAs because the liquidity insurance provided by guaranteed surrender values is highly valued by European households.

[28]For instance, French regulation allows regulators to temporarily suspend surrender payouts to strengthen financial stability.

option moves toward the money and, thus, policyholders have stronger incentives to surrender. Thus, surrender options amplify the convexity of life insurance contracts, namely the decline in their duration when interest rates rise.

We empirically document the impact of interest rates on surrenders in a large panel of German life insurers. Using U.S. monetary policy surprises as an instrument for German government bond rates, we provide causal evidence that higher interest rates raise surrender rates. Exploiting heterogeneity in surrender incentives across insurance companies, we argue that this effect is due surrender options moving toward the money.

A sufficiently strong increase in surrender rates can force life insurers to sell assets, thereby generating downward pressure on asset prices. We calibrate a granular model to estimate surrender-driven asset sales and their price impact. The volume of asset sales increases with a longer duration of insurers' assets, which prevents policyholders from benefiting from rising interest rates and, thereby, amplifies surrender rates. If insurers matching the duration of their investments to insurance contracts, they predominantly sell long-term rather than short-term assets. These asset sales occur swiftly after interest rates begin to rise and subside after roughly 5 years. Instead, if insurers target constant portfolio weights, mostly short-term assets are sold, and the volume of asset sales increases over time. These results highlight insurers' investment strategy as an important determinant of the level, timing, and allocation of surrender-driven asset sales.

We discuss several empirical predictions of our model and policy implications. In a counterfactual calibration, we show that market value adjustments, which (partly) align surrender values with asset prices, lower the sensitivity of surrender incentives to interest rate changes. Therefore, market value adjustments can be a viable tool to mitigate surrender-driven asset sales.

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Internet Appendix for "Life Insurance Convexity" *

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*The views expressed in this paper are the authors' and do not necessarily reflect those of the European Central Bank or the Eurosystem.

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A Surrender Options in the U.S.

In the U.S., surrender payouts are similarly large as in Europe, amounting to EUR 308 billion (equivalently, \$345 billion) in 2019, which corresponds to roughly 44% of total life insurance payouts (NAIC, 2020). U.S. life insurance products with cash value also entail surrender options. These products include universal life and whole life insurance as well as variable and deferred annuities (Berends et al., 2013).

For individual deferred annuities, the surrender value is mandated to correspond to at least 87.5% of the accumulated gross cash value up to the surrender date and additional interest credits less surrender charges (NAIC, 2017). Similar to German life insurance policies, the guaranteed minimum interest rate is determined at contract origination.[1] Therefore, there exists a minimum guaranteed surrender value that is independent of market developments.

For multi-year deferred annuities, the surrender value is typically subject to a market value adjustment (MVA), at least in the first contract years. This can cause both upward and downward changes based on market developments (NAIC, 2021). The MVA compares interest rates at contract origination with rates at the surrender date. If interest rates have increased (decreased) during the active contract period, the effect of the MVA on the surrender value will be negative (positive), i.e., the policyholder will receive relatively less (more).

Variable annuities come with a broad flexibility for policyholders to decide on the underlying investment (typically mutual funds) and on guarantee components (Koijen and Yogo, 2022). Depending on the chosen financial guarantee, surrender values may react less sensitive to an interest rate rise than the underlying investment, which strengthens surrender incentives similarly as for the contracts we study in our model.

Surrender penalties for U.S. life insurance contracts are typically up to 10% of the con-

[1] The guaranteed minimum interest rate must be between 1 and 3% and, within this range, depends on the five-year U.S. Constant Maturity Treasury yield reduced by 125 bps (NAIC, 2017).

tract's cash value in the first year and then decrease by 100 bps annually. However, 10% of the cash value can typically be withdrawn without a penalty in the first contract years.

B Anecdotal Evidence

Anecdotal evidence emphasizes the interaction of market interest rates, surrender options, and life insurers' liquidity risk. We highlight three historical examples. First, in response to rising U.S. market interest rates in the late 1970s and early 1980s, U.S. surrender rates increased sharply from roughly 3% in 1951 to 12% in 1985 (Kuo et al., 2003). As a result, U.S. life insurers liquidated a large share of their investments (Russell et al., 2013).

Second, the surrender of guaranteed investment contracts (GICs), which are savings contracts with financial guarantees resembling modern savings contracts, significantly contributed to U.S. life insurer failures in the 1990s (Brewer et al., 1993; Jackson and Symons, 1999; Brennan et al., 2013). Rising interest rates in particular sparked mass surrenders of GICs sold by *General American*, a U.S. life insurer, resulting in its failure in 1999 (Fabozzi, 2000; Brennan et al., 2013).

Third, rising interest rates also triggered large surrenders in South Korea in 1997–1998. As interest rates sharply rose (by approximately 4 ppt for 5-year government bonds within a few months), annualized surrender rates increased from 11% to 54.2% for long-term savings contracts, and life insurers' gross premium income fell by 26%. Life insurers were forced to liquidate assets, and approximately one-third of them exited the market (Geneva Association, 2012).

C Empirical Analysis: Data and Additional Results

C.1 Data

Table IA.1. Variable definitions and data sources.

Note: *BaFin* refers to data retrieved from the "Erstversichererstatistik" of the German financial supervisory authority *BaFin*, available either in print or online at `https://www.bafin.de/DE/PublikationenDaten/Statistiken/Erstversicherung/erstversicherung_artikel.html`. *GDV* refers to data shared with us by the German association of insurers.

Variable	Definition
Insurer-Year level	
Surrender rate	Fraction of life insurance contracts surrendered weighted by contract volume (*Source: BaFin*)
New business	Volume of new insurance business relative to that of total insurance business at the previous year's end (*Source: BaFin*)
Year level	
Interest rate	10-year German government bond rate (*Source: Bundesbank*)
Guaranteed return	Annually guaranteed minimum return for new German life insurance contracts (*Source:* *http://gdv.de*)
log(New German contracts)	Logarithm of the number of new German life insurance contracts (*Source: GDV*)
New term life	Fraction of new term life insurance contracts relative to all new life insurance contracts in Germany (*Source: GDV*)
Inflation	Annual change in German CPI (*Source: BIS*)
GDP growth	Annual change in German GDP (*Source: OECD*)
Investment growth	Annual change in German investment (*Source: OECD*)
Crisis	Indicator for banking crises (*Source: Laeven and Valencia (2018)*)
MoPoSurp	End-of-year cumulative U.S. monetary policy shocks, computed as the sum of past monetary policy surprises (since 1990), which are defined following Jarocínski and Karadi (2020) as the first principal component of the surprises in interest rate derivatives with maturities from 1 month to 1 year, which are measured as described in Gürkaynak et al. (2005) (*Source:* *http://marekjarocinski.github.io*)
Pure MoPoSurp	End-of-year cumulative U.S. monetary policy shocks (since 1990) purged of central bank information shocks with simple ("Poor Man's") sign restrictions as described by Jarocínski and Karadi (2020) (*Source:* *http://marekjarocinski.github.io*)

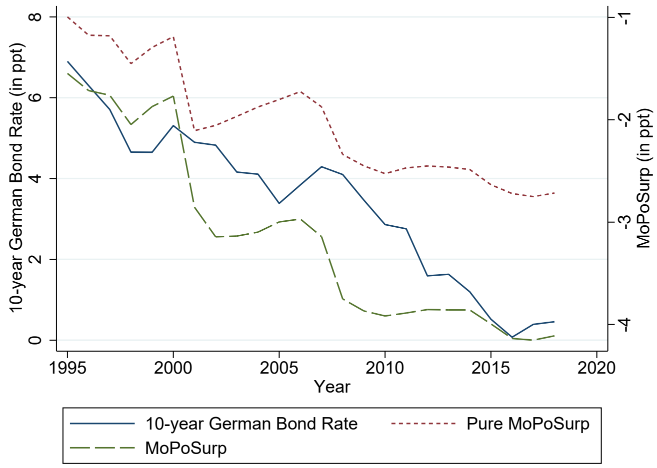
Continued on next page

Table IA.1 – *Continued from previous page*

Variable	**Definition**
CB InfoSurp	End-of-year cumulative U.S. central bank information shocks (since 1990) obtained using simple ("Poor Man's") sign restrictions as described by Jarocínski and Karadi (2020) (*Source:* `http://marekjarocinski.github.io`)
%U.S. Imports	U.S. Imports of Goods by Customs Basis from Germany / (U.S. Imports of Goods by Customs Basis from Germany + U.S. Exports of Goods by F.A.S. Basis to Germany) (*Source: FRED St. Louis*)

Figure IA.1. German government bond rates and U.S. monetary policy surprises.

The figure plots the evolution of the 10-year German government bond rate (left axis), cumulative monetary policy surprises (right axis), and pure cumulative monetary policy surprises (right axis), which are purged from central bank information surprises following Jarocínski and Karadi (2020), from 1995 to 2018.



When processing data from BaFin's Erstversichererstatistik, we use the following conventions:

1. We translate values from the historical German currency ("Deutsche mark") to the euro for the years 1995 to 2000 using the official exchange rate 1 EUR = 1.95583 Deutsche marks.
2. The level of insurance in force is computed as the final payout at maturity assuming that the current cash value and future premiums grow at the minimum guaranteed return in future years.
3. We follow BaFin's definition of the overall surrender rate and compute it for years $t \leq 2015$ as

$$\bar{\lambda}_{i,t} = \frac{\text{insurance in force}_{i,t-1} \cdot \lambda_{i,t}^{\text{late}} + \text{new business}_{i,t-1} \cdot \lambda_{i,t}^{\text{early}}}{(\text{insurance in force}_{i,t-1} + \text{insurance in force}_{i,t})/2},$$

where insurance in force$_{i,t-1}$ is insurance in force at year-end $t-1$ or, equivalently, insurance in force at year-begin t of insurer i, and $\lambda_{i,t}^{\text{early}}$ and $\lambda_{i,t}^{\text{late}}$ are the surrender rates for new and old business, respectively.

4. To construct the annual German government bond rate, we retrieve end-of-month yields from the German Bundesbank and take annual averages.

C.2 Additional Results

Table IA.2. Surrender Rates and Interest Rates: Robustness.
This table presents estimates from regressions of insurer-level annual surrender rates on the 10-year German government bond rate from 1996 to 2019. Columns (1) to (4) are based on the model

$$\text{Surrender rate}_{i,t} = \alpha \cdot \text{Interest rate}_{t-1} + \beta \cdot \text{New business}_{i,t-1} + \xi \cdot Y_{t-1} + u_i + \varepsilon_{i,t}.$$

Column (1) uses pure monetary policy surprises as an instrument for 10-year German government bond rates and additionally controls for central bank information shocks. Column (2) uses the 10-year U.S. treasury rate as an instrument for 10-year German government bond rates. Columns (3) and (4) present reduced-form estimates. Columns (1) to (3) control for the lagged share of U.S. imports from Germany relative to the sum of U.S. imports and U.S. exports from/to Germany in addition to the controls in Table 2. Column (4) additionally controls for the 10-year German government bond rate. Columns (5) and (6) regress annual changes in surrender rates on annual changes in the 10-year German government bond rate, both from $t-1$ to t, in the following specification:

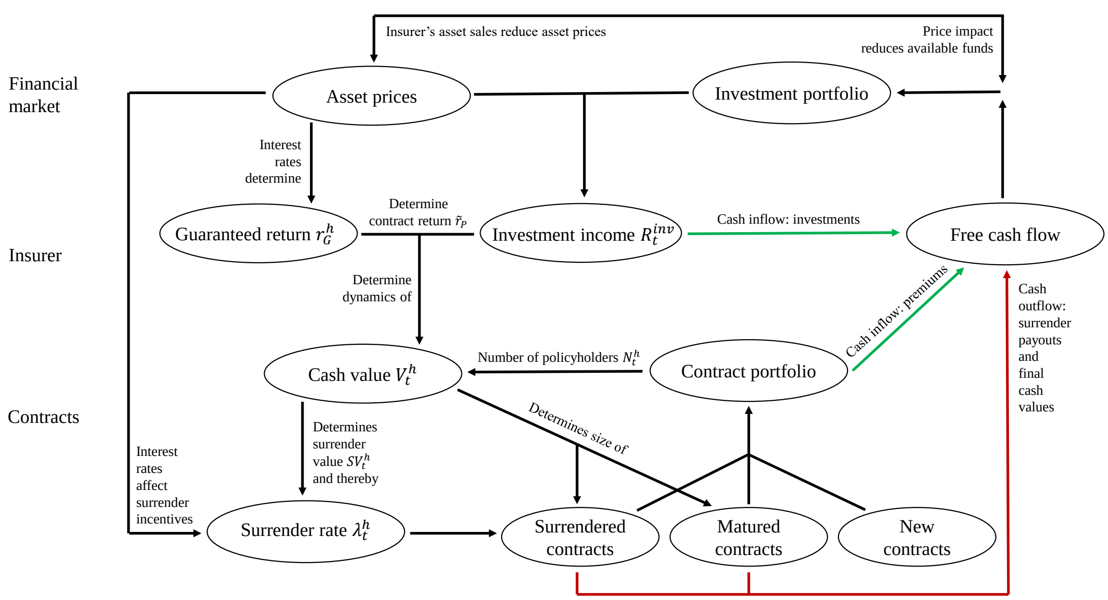
$$\Delta\text{Surrender rate}_{i,t} = \alpha \cdot \Delta\text{Interest rate}_t + \beta \cdot \text{New business}_{i,t-1} + \xi \cdot Y_{t-1} + u_i + \varepsilon_{i,t}.$$

$1\{\Delta\text{Interest rate}_t > 0\}$ is an indicator for an increase in the 10-year German government bond rate from $t-1$ to t. The sample is at the insurer-by-year level from 1996 to 2019. Y_{t-1} is a vector with the same macroeconomic control variables as in Table 2. Detailed variable definitions and data sources are reported in the Internet Appendix. t-statistics are shown in brackets, based on standard errors that are clustered at the insurer level. ***, **, * indicate significance at the 1%, 5% and 10% level.

	(1)	(2)	(3)	(4)	(5)	(6)
Dependent variable:	Surrender rate				ΔSurrender rate	
	IV		OLS			
Interest rate$_{t-1}$	0.236***	0.293***		0.330***		
	[3.36]	[5.57]		[5.96]		
CB InfoSurp$_{t-1}$	0.062					
	[0.21]					
%U.S. Imports$_{t-1}$	1.254	2.451	-1.834			
	[0.84]	[1.33]	[-1.49]			
MoPoSurp$_{t-1}$			0.334***	-0.185		
			[3.96]	[-1.40]		
ΔInterest rate$_t$					0.166***	0.149**
					[4.55]	[2.20]
$1\{\Delta\text{Interest rate}_t > 0\} \times \Delta\text{Interest rate}_t$						0.503**
						[2.57]
$1\{\Delta\text{Interest rate}_t > 0\}$						-0.147
						[-1.60]
Macro controls	Y	Y	Y	Y	Y	Y
New business$_{i,t-1}$	Y	Y	Y	Y	Y	Y
Insurer FE	Y	Y	Y	Y	Y	Y
First stage						
Pure MoPoSurp$_{t-1}$	2.25***					
	[182.54]					
U.S. treasury rate$_{t-1}$		0.96***				
		[242.62]				
F Statistic	4,314	5,680				
No. of obs.	2,234	2,234	2,234	2,234	2,048	2,048
No. of insurers	159	159	159	159	150	150

D Model and Calibration Details

Figure IA.2. Illustration of Model Ingredients and Dynamics.
The financial market model determines asset prices and, in particular, government bond rates, which determine the guaranteed return for the new cohort of contracts in year h, r_G^h. Jointly with the insurer's investment portfolio, asset prices also determine the insurer's investment income R_t^{inv}. A fraction ξ of the investment income is passed on to policyholders. The maximum of the guaranteed return and the policyholder's fraction of the investment income determines the contract return $\tilde{r}_P$, which drives the dynamics of life insurance contracts' cash value V_t^h. The cash value determines the surrender value SV_t^h. Surrender decisions are based on comparing SV_t^h with current interest rates, resulting in the surrender rate λ_t^h. Cash values also determine the size of surrendered and matured contracts. Contract portfolio dynamics are jointly determined by the volume of surrendered, matured, and new contracts and, thereby, reflected in the number of policyholders N_t^h of cohort h. The insurer's total free cash flow is given by the sum of investment income and premiums net of cash outflows due to surrendered and matured contracts. Excess cash is reinvested, whereas a negative free cash flow forces the insurer to sell assets. Asset sales reduce asset prices and, thereby, negatively impact the funds available for reinvestment.



D.1 Contract Return Dynamics

The annual contract return is given by

$$\tilde{r}_{P,t+1}^h = \max\{r_G^h,\, \tilde{r}_{t+1}^*\}. \tag{IA.1}$$

r_G^h is a cohort h's guaranteed minimum rate of return, which is fixed at contract origination h for the entire contract life. Following German regulation, we assume that r_G^h is annually adjusted (for new cohorts) and tracks 60% of the 10-year moving average of 10-year German government bond rates in 50 bps steps (Eling and Holder, 2013).[2]

$\tilde{r}^*_{t+1}$ reflects the profit participation component of the contract. Premiums are jointly invested at the insurer level. Policyholders receive a fraction $\xi \in (0, 1)$ of the insurer's total investment income R^{inv}_{t+1} allocated relative to cash values, such that the profit participation rate is

$$\tilde{r}^*_{t+1} = \xi \frac{R^{inv}_{t+1}}{\sum_h V_t^h}. \tag{IA.2}$$

The investment income R^{inv}_{t+1} is determined by historical cost accounting. It is the sum of bond coupon payments, stock dividends, and rents less depreciations.

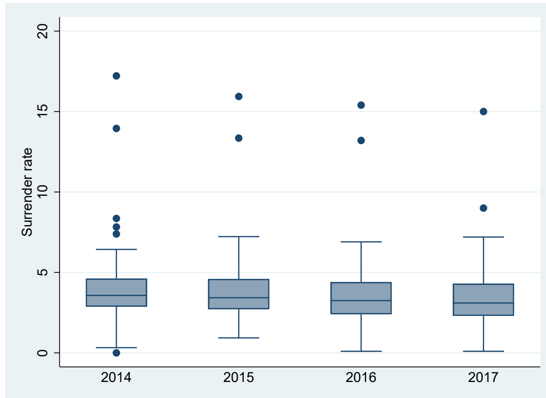
D.2 Calibration of Surrender Decisions

We calibrate the model of surrender decisions described in Section 3.1.2 by exploiting the data on German life insurers' surrender rates described in Section 2. The initial date in the model, $t = 0$, corresponds to year-end 2015. We focus on calibrating the cross-section of surrender rates in the first period, corresponding to 2016, which will imply the sensitivity of surrender rates. Since the data distinguish between early and late surrender rates only until 2015, we use the data from 2015. In Figure IA.3, we show that the distribution of the insurer-level surrender rate is similar in 2015 and 2016, which is consistent with the German

[2]Regulators in many countries set maximum levels for guaranteed returns that depend on long-term interest rate averages. German insurers have typically offered guaranteed returns equal to this maximum level. German law specified 60% of the 10-year yield on AAA-rated European government bonds as the maximum guaranteed return until 2015 (§65 Insurance Supervision Act). Since 2015 the calculation of this cap is unspecified (§88 Insurance Supervision Act). However, the German regulator has not deviated significantly from the historical rule. For example, our model predicts that the guaranteed return would be lowered in 2017, which matches the realized (maximum) guaranteed return.

economic environment, and interest rates in particular, being very stable in these years.

Figure IA.3. Distribution of Surrender Rates across German Life Insurers.



We calibrate the model's parameters β_0, β_1, and β_2 as follows, with the aim of making as few additional assumptions about the distribution of surrender rates as possible:

(1) The insurer's overall surrender rate (weighted across cohorts by the volume of insurance in force) in the first year of the model matches the surrender rate of the median German life insurer in 2015 (weighted across insurers by contract portfolio size), which is 3.34%.

(2) To calibrate the sensitivity to contract age, we assume that the surrender rate of contracts in their first year given the average German life insurer's contract return and the 30-year German government bond rate in 2015 (which were 3.16% and 1.225%, respectively; we use the 30-year bond rate since the Bundesbank does not report yields for longer maturities) equals the *early* surrender rate of the median German life insurer in 2015 (weighted across insurers by contract portfolio size), which is 6.3%,

$$\lambda^h_{h+1} = 1 - \Phi\left(\beta_0 + \beta_1 \log\left(\vartheta^{-1}\left(\frac{1+0.0316}{1+0.01225}\right)^{40}\right) + \beta_2 \log(2)\right) \overset{!}{=} 0.063. \qquad \text{(IA.3)}$$

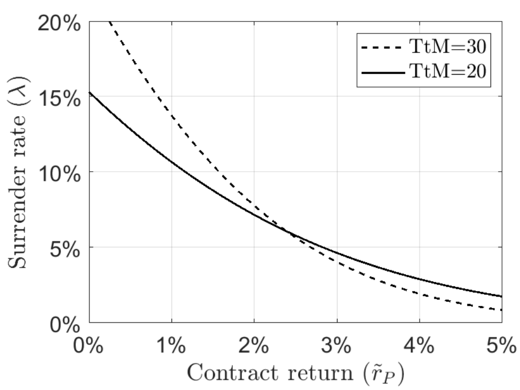
(3) To calibrate the sensitivity to contract returns, we match the surrender rate of contracts in their first year whose contract return matches the German government bond rate with the *early* surrender rate of insurers whose investment return matches the German

government bond rate, assuming that the observed investment return is a reasonable proxy for contract returns.[3] We approximate the latter by considering the median early surrender rate in 2015 (weighted across insurers by contract portfolio size) among those insurers with the 10% smallest difference between investment return and 30-year government bond rate, which is 24.6%. The resulting condition is:

$$\lambda_{h+1}^{h} = 1 - \Phi\left(\beta_0 + \beta_1 \log\left(\vartheta^{-1}\right) + \beta_2 \log(2)\right) \stackrel{!}{=} 0.246. \tag{IA.4}$$

The resulting calibration is $(\beta_0, \beta_1, \beta_2) = (0.4933, 1.1129, 0.2390)$ and is illustrated in Figure IA.4.

Figure IA.4. Surrender Rate Calibration.
The figure depicts the surrender rate for a 40-year savings contract as a function of the contract return $\tilde{r}_P$ and for different times to contract maturity, TtM, of 30 and 40 years. In the figure, we assume a flat risk-free rate of $r_f = 1.22\%$, corresponding to the 10-year German government bond yield in 2015, and a surrender penalty equal to $1 - \vartheta = 2.5\%$.



D.3 Accounting of Insurance Liabilities

Under European statutory accounting following the Solvency II regulation, insurance liabilities reflect the market-consistent value of contracts. For this purpose, insurers compute

[3] Note that the investment return is a reasonable proxy for the contract return particularly for contracts sold in 2015 since their guarantee was below insurers' investment returns. For example, the average (contract portfolio-weighted) investment return was 2.5% in 2015 (according to BaFin), and the average profit participation rate was 3.16% (according to Assekurata, 2016), while the guaranteed return for new contracts was 1.25%.

a *best estimate* of market-consistent contract values. We compute the Solvency II balance sheet mainly to scale our model to the size of European life insurers. We approximate the value of liabilities in cohort h at time t on the Solvency II balance sheet as follows:

$$PV_t^h = V_t^h \left(\sum_{j=1}^{T^h - t} \frac{\vartheta \lambda_t^h (1-\lambda_t^h)^{j-1} \prod_{h=1}^{j-1} \hat{r}_{P,t+h}^h}{(1-r_{f,t,j-1})^{j-1}} + \frac{(1-\lambda_t^h)^{T^h-t} \prod_{h=1}^{T^h-t} \hat{r}_{P,t+h}^h}{(1+r_{f,t,T^h-t})^{T^h-t}} \right). \qquad \text{(IA.5)}$$

Here, we make two assumptions. The first is that the most recent realized surrender rate λ_t^h in cohort h is used for future years. The second is that the predicted contract return for year $t+h$, $\hat{r}_{P,t+h}^h$, is estimated from a fitted log-linear model. In particular, at each year, the investment return $\tilde{r}_t^*$ is fitted to a log-linear model, which is then used to predict future investment returns: $\tilde{r}_i^* = \alpha + \beta \log(10+i-t) + \varepsilon_i$, which is fitted using OLS based on observations from the past 10 years, $i = t-9, ..., t$. Then, the predicted investment return is given by $\hat{r}_i^* = \hat{\alpha} + \hat{\beta} \log(10+i-t)$ for $i > t$.

D.4 Calibration of the Initial Contract Portfolio

To calibrate the initial cash value of contract cohorts, we use the following data:

- the volume of life insurance savings contracts (“Kapitalversicherungen”) newly issued in year h, N^h, obtained from the German insurance association, GDV (in million EUR)[4],
- the life insurance sector’s surrender rate, $\tilde{\lambda}_t$,
  - 1996–2015: for the median German life insurer (weighted across insurers by contract portfolio size) according to BaFin’s Erstversichererstatistik
  - 1976–1995: the average surrender rate reported by the German insurance association, GDV, scaled by the ratio of the BaFin surrender rate to the GDV surrender rate from 1996 to account for differences in the underlying set of life insurers

[4]We thank the GDV for sharing the data with us.

- the realized contract return of German life insurance contracts
  - 1996–2015: reported by Assekurata, a rating agency for German life insurers[5]
  - 1976–1995: predicted by fitting a linear model to the average contract return reported by Assekurata for 1996–2015 using the 10-year moving average of 5-year German government bond rates reported in the IMF's International Financial Statistics as explanatory variable (the R^2 is 91%). We use bond rates from the IMF's statistics because of their long available history.

Since the surrender rate and contract return are not available at the cohort level, we make the following assumptions: (1) within each cohort h, each contract pays a premium of EUR 1 each year if not surrendered or matured, (2) each contract has a lifetime of 40 years at inception, and (3) each contract's surrender rate in year t can be approximated by the average surrender rate $\tilde{\lambda}_t$. However, accumulating contracts since 1976 according to these assumptions must not necessarily arrive at the representative contract portfolio in 2015. Instead, contract dynamics might have deviated in practice due to the presence of one-time premiums, heterogeneity in the surrender rate and contract return, and time-varying insurance supply.

To evaluate the representativeness of the initial contract portfolio, we use two key portfolio characteristics: the average guaranteed return per contract and the portfolio's modified duration.[6] Assekurata (2016) reports an average guaranteed return of 2.97% for German

[5]We thank Assekurata for sharing the data with us.

[6]Consistent with EIOPA, 2016, we calculate a cohort's modified duration as

$$\frac{V_t^h}{(1+r_{f,t,T^h-t})PV_t^h}\left(\sum_{j=1}^{T^h-t}(j-1)\frac{\vartheta\lambda_t^h(1-\lambda_t^h)^{j-1}\prod_{h=1}^{j-1}\hat{r}_{P,t+h}^h}{(1-r_{f,t,j-1})^{j-1}}+(T^h-t)\frac{(1-\lambda_t^h)^{T^h-t}\prod_{h=1}^{T^h-t}\hat{r}_{P,t+h}^h}{(1+r_{f,t,T^h-t})^{T^h-t}}\right),$$

where

$$PV_t^h=V_t^h\left(\sum_{j=1}^{T^h-t}\frac{\vartheta\lambda_t^h(1-\lambda_t^h)^{j-1}\prod_{h=1}^{j-1}\hat{r}_{P,t+h}^h}{(1-r_{f,t,j-1})^{j-1}}+\frac{(1-\lambda_t^h)^{T^h-t}\prod_{h=1}^{T^h-t}\hat{r}_{P,t+h}^h}{(1+r_{f,t,T^h-t})^{T^h-t}}\right)$$

is the present value of contract cash flows at year-end t and $\hat{r}_{P,t+h}^h$ is the predicted contract return for year $t+h$ as described in Section D.3.

life insurers in 2015. The German association of insurers reports a modified duration of 14.1 years for the median German life insurer. Following the assumptions above, our initial portfolio would exhibit a much shorter duration. In this case, the portfolio weight of older contracts (with a short remaining time to maturity and, thus, short duration) is too large. To offset this bias, we modify the size of cohorts $h \in \{-39, ..., 0\}$ as follows:

$$\hat{N}^h = \left[N^h \left(1 + g \cdot (h + T^h)\right)\right].$$

The larger the adjustment factor g, the larger is the volume of younger relative to older contracts. This increases the modified duration. We find that $g = 10$ lifts the modified duration to 14.1 years, closely matching the reported duration. The implied average guaranteed return is 3.12%, which is close to that reported by Assekurata (2016) and, thus, provides additional support for our calibration strategy. Finally, we scale $\hat{N}^h$ by dividing it by $\hat{N}^0/10,000$ such that the implied number of new contracts at $t = 0$ is equal to $10,000$.

D.5 Calibration of the Insurer's Investment Portfolio

We calibrate the insurer's asset portfolio weights based on GDV (2016), according to which German life insurers held 6.7% in stocks (shares and participating interests) and 3.9% in real estate in 2015. For the corporate bond portfolio weight, we aggregate German life insurers' investments in 2015 in mortgages (5.8%), loans to credit institutions (9.8%), loans to companies (1%), contract and other loans (0.5%), corporate bonds (10.3%), and subordinated loans and profit participation rights, call money, time and fixed deposits and other bonds and debentures (6.7%), which results in 34.1% and coincides with the fraction of corporate bonds reported by the EIOPA (2014) for German insurers. We allocate the remaining fraction of fixed-income instruments to government bonds (55.3%).

The weights within subportfolios are based on Berdin et al. (2017) and EIOPA (2014) and reported in Table IA.3. We include a large home bias toward German government bonds, which, however, has little impact on our results. Due to the absence of more granular data, we calibrate real estate and stock weights to yield a plausible home bias of 60% for German real estate and stocks and equally distribute the remaining weights.

Bond maturities differ within the insurer's portfolio, such that within each bond category, the oldest bond is due in 1 year, the youngest government bond is due in 20 years, and the youngest corporate bond is due in 10 years, reflecting the longer duration of government bonds in insurers' portfolios. Bond coupons are based on the (government or corporate) bond yield at bond issuance.

Table IA.3. Investment Portfolio Allocation.
The table depicts the weights and average modified duration of each asset class in the insurer's investment portfolio. The calibration is based on EIOPA (2014, 2016) and GDV (2016).

Entire Investment Portfolio	**Weight**	**Duration**
Government Bonds	55.3%	10.4
Corporate Bonds	34.1%	7.5
Stocks	6.7%	-
Real Estate	3.9%	-
Government Bond Portfolio	**Weight**	**Modified Duration**
German/All Government Bonds	90.4%	10.45
French/All Government Bonds	2.4%	10.12
Dutch/All Government Bonds	2.4%	10.45
Italian/All Government Bonds	2.4%	8.03
Spanish/All Government Bonds	2.4%	10.45
Corporate Bond Portfolio	**Weight**	**Duration**
AAA/All Corporates	23.6%	7.36
AA/All Corporates	16.85%	8.08
A/All Corporates	33.71%	7.65
BBB/All Corporates	25.84%	7.22

To calibrate the modified duration of different asset classes, we use 9.3 years as a benchmark duration for the fixed-income portfolio, based on the stress test results in EIOPA (2016, Table 6) (9.6 years for 2015) and EIOPA (2014) (8.2 years for 2013). EIOPA (2014) reports an average duration of 9.5 years for government and 6.9 years for corporate bonds for 2013.

We scale these durations up to the average value reported in EIOPA (2016, Table 12) for 2015, implying the scaling factor $\hat{w}_{2015} = \frac{9.3}{(6.9 w_{\text{corp}} + 9.5 w_{\text{sov}})/(w_{\text{corp}} + w_{\text{sov}})} \approx 1.09$. To calibrate heterogeneity within the government bond portfolio, we use the distribution of the modified duration of government bonds across countries reported in EIOPA (2016, Table 13) and scale these up to match the average government bond portfolio duration of $9.5 \cdot \hat{w}_{2015} = 10.4$. Similarly, to calibrate heterogeneity within the corporate bond portfolio, we use the distribution of modified durations of corporate bonds across ratings reported in EIOPA (2016, Table 14) and scale these up to match the average corporate bond portfolio duration of $6.9 \cdot \hat{w}_{2015} = 7.5$. The final allocation of bonds across ratings is skewed toward higher-rated assets, consistent with Assekurata (2016).

Given the duration of individual bonds and the target duration of each asset class, we determine portfolio weights following the methodology in Berdin et al. (2017), which assumes that individual bonds' portfolio weights are an exponential function of their remaining time to maturity, and we correct for potential deviations from the target duration by minimizing the square of the difference between target and actual duration starting with the Berdin et al. (2017)-implied weights.

D.6 Calibration of the Short-Rate Model

Short rate dynamics are given by

$$dr_t = \alpha_r(\theta_r - r_t)dt + \sigma_r dW_t^r, \tag{IA.6}$$

where r_t is the short rate at time t, W_t^r is a standard Brownian motion, $\alpha_r > 0$ is the speed of mean reversion, $\sigma_r > 0$ is the volatility, and θ_r is the level of mean reversion. Under the assumption of arbitrage-free interest rates, Equation (IA.6) specifies the term structure of annually compounded interest rates at time t for maturities τ, $\{r_{f,t,\tau}\}_{\tau \geq 0}$. Following Brigo and Mercurio (2006), the price of a zero-coupon bond at time t with maturity at $t+\tau \geq t$ is

$$(1+r_{f,t,\tau})^{-\tau} = A(\tau)e\left[-B(\tau)r_t\right], \tag{IA.7}$$

where

$$B(\tau) = \frac{1}{\kappa_r}\left(1 - exp\left[-\kappa_r \tau\right]\right)$$

and

$$A(\tau) = exp\left[(\theta_r - \frac{\sigma_r^2}{2\kappa_r^2})(B(\tau)-\tau) - \frac{\sigma_r^2}{4\kappa_r}B(\tau)\right],$$

and $r_{f,t,\tau}$ is the annually compounded interest rate at time t.

We calibrate the short rate volatility σ_r using a maximum-likelihood estimator based on the monthly Euro OverNight Index Average (EONIA) from December 2000 to November 2015.[7] To calibrate κ_r and θ_r, we additionally use the whole term structure of German government bond rates. For this purpose, we use the least squares estimate for κ_r and θ_r comparing the term structure for bonds with a maturity from 1 to 20 years implied by the historical evolution of EONIA and the parameters σ_r, κ_r and θ_r with the actual term structure of German government bond rates. The resulting parameters are $\sigma_r = 0.0052$, $\kappa_r = 0.0813$, $\theta_r = 0.018$. The initial level of the short rate is $r_0 = -0.002$, which is the level of EONIA on December 31, 2015.

[7]EONIA is the weighted rate for the overnight maturity, calculated by collecting data on unsecured overnight lending in the euro area provided by banks belonging to the EONIA panel. Data source: *ECB Statistical Data Warehouse*.

D.7 Calibration of the Financial Market Model

Spreads for government and corporate bonds are modeled by Ornstein-Uhlenbeck processes, analogously to the short rate,

$$ds_t^j = k^j(\overline{s}^j - s_t^j)dt + \sigma^j dW_t^j. \tag{IA.8}$$

Therefore, $\{r_{f,t,\tau} + s_t^j\}_{\tau \geq 0}$ is the term structure of bonds of type j at time t.

We calibrate bond spreads and stock and real estate returns based on monthly data from December 2000 to November 2015. Corporate bond rates are given by the effective yield of the AAA/AA/A/BBB-subset of the ICE BofAML US Corporate Master Index (obtained from *FRED St. Louis*), which tracks the performance of U.S. dollar-denominated investment-grade rated corporate debt publicly issued in the U.S. domestic market. To account for the different inflation (expectations) between the EU and U.S., we calculate bond spreads with respect to the yield of U.S. treasuries with a maturity of 10 years (obtained from *FRED St. Louis*).[8] Government bond spreads are calibrated based on the spread relative to German bond rates from December 2000 to November 2015 (obtained from *Thomson Reuters Eikon*), averaged across maturities from 1 to 20 years.

Table IA.4 describes the sample of bond spreads. Note that we retrieve bond rates (and spreads) for maturities of 1 to 20 years for each government bond, while corporate bond spreads are calculated by comparing the effective yield of the ICE BofAML US Corporate Index to the 10-year yield. We assume that the credit spread is the same across maturities for each bond type and, thus, we calibrate the spread process $\{s_t^j\}_t$ for the average spread across maturities in the case of government bonds. Parameter estimates are based on maximum likelihood and reported in Table IA.4. We assume that coupons are equal to the (government or corporate) bond yield at issuance. Given coupons, we price bonds using the term structure

[8] The results are similar if we take German government bond rates instead.

of risk-free rates $r_{f,\tau,t}$ and spreads s_t^j.

Table IA.4. Summary Statistics and Calibration of Bond Spreads.
The table reports summary statistics and maximum-likelihood estimates for the long-term mean ($\bar{s}$), speed of mean reversion (k), and volatility (σ) of the Ornstein-Uhlenbeck process $s^j(t) = k^j(\bar{s}^j - s^j(t))dt + \sigma^j dW^j(t)$ for monthly bond spreads between (a) government bond rates and German government bonds and (b) corporate bond rates and the 10Y U.S. treasury bond rate from December 2000 to November 2015. Government bond rates include observations for 1-year to 20-year maturities, and the calibration is based on the average spread across maturities. Corporate bond spreads are based on the effective yield of ICE BofAML US Corporate Indices and 10-year U.S. treasury rates. *Source: Authors' calculations, Thomson Reuters Eikon (government bonds), FRED St. Louis (corporate bonds).*

Name	# Observations	Mean	Sd	p25	p75	$\bar{s}$	k	σ
French	180	0.003188	0.003176	0.0006895	0.004495	0.003593	0.3574	0.00265
Dutch	180	0.002085	0.001711	0.000651	0.003148	0.002172	0.5086	0.001716
Italian	180	0.01158	0.01214	0.002454	0.016	0.01375	0.2018	0.007465
Spanish	180	0.01086	0.01343	0.000667	0.01692	0.01493	0.1497	0.007071
AAA	180	0.003421	0.006385	-0.0005	0.0057	0.003081	1.09	0.009236
AA	180	0.004504	0.008326	-0.00065	0.0069	0.003427	0.5738	0.008593
A	180	0.009906	0.01017	0.0046	0.01115	0.00832	0.4922	0.009814
BBB	180	0.01847	0.01154	0.0119	0.0215	0.0174	0.5289	0.01164

Stocks and real-estate investments follow geometric Brownian motions (GBMs) that are calibrated to the STOXX Europe 600 index and MSCI Europe real estate index, respectively (retrieved from *Thomson Reuters Eikon*). Table IA.5 reports the descriptive statistics for monthly log-returns. We calibrate the GBM drift and volatility with maximum-likelihood estimates for monthly log-returns, which are also reported in Table IA.5. Stocks pay dividends, and real estate investments pay rents at each year's end. Dividends and rents are assumed to equal the maximum of zero and 50% of the annual return.

Table IA.5. Summary Statistics and Calibration for Stocks and Real Estate.
The table reports summary statistics and maximum-likelihood estimates for geometric Brownian motions for monthly stock and real estate returns from December 2000 to November 2015. Stock returns are based on the STOXX Europe 600 index, and real estate returns are based on the MSCI Europe real estate index. *Source: Authors' calculations, Thomson Reuters Eikon.*

Name	# Observations	Mean	Sd	p25	p75	GBM Drift	GBM Volatility
Stocks	180	0.0001462	0.04879	-0.02109	0.03055	0.01604	0.169
Real Estate	180	0.003853	0.07032	-0.03085	0.04264	0.0759	0.2436

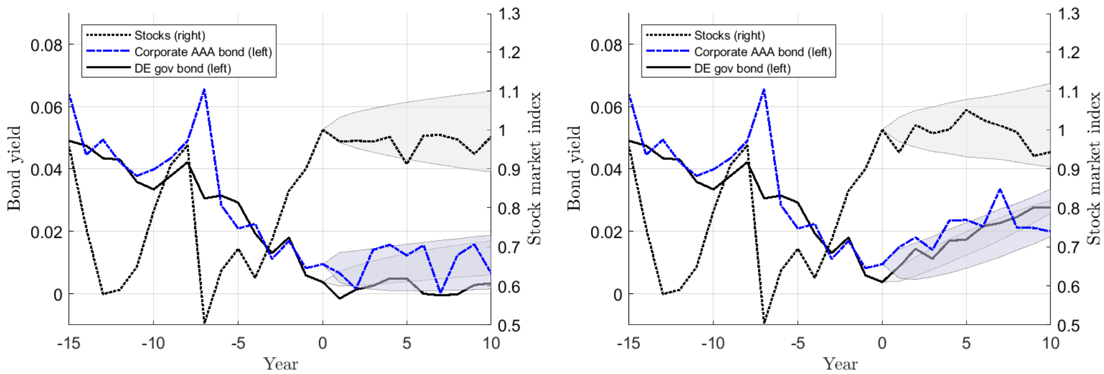
Finally, we correlate all stochastic processes via a Cholesky decomposition of their diffusion terms. Table IA.6 reports the correlation coefficients based on monthly residuals after fitting bond spreads, stock and real estate returns.

Table IA.6. Correlation Matrix for Financial Market Processes.

The table reports the correlation coefficients for monthly residuals from December 2000 to November 2015 of the short rate (EONIA), government bond spreads for France (FR), the Netherlands (NL), Italy (IT), and Spain (ES), corporate bond spreads for AAA-, AA-, A-, and BBB-rated bonds, stocks, and real estate returns, after fitting to the short rate and spreads to Ornstein-Uhlenbeck processes and stocks and real estate returns to geometric Brownian motions.

	EONIA	Spread (FR)	Spread (NL)	Spread (IT)	Spread (ES)	Spread (AAA)	Spread (AA)	Spread (A)	Spread (BBB)	Stocks	Real Estate
EONIA	1	-0.114	-0.133	-0.103	-0.072	-0.073	0.052	0.039	-0.112	0.135	0.274
Spread (FR)	-0.114	1	0.535	0.67	0.629	0.136	0.267	0.284	0.253	-0.174	-0.203
Spread (NL)	-0.133	0.535	1	0.489	0.518	0.278	0.311	0.33	0.368	-0.243	-0.27
Spread (IT)	-0.103	0.67	0.489	1	0.81	0.142	0.277	0.296	0.293	-0.21	-0.196
Spread (ES)	-0.072	0.629	0.518	0.81	1	0.154	0.242	0.252	0.231	-0.147	-0.141
Spread (AAA)	-0.073	0.136	0.278	0.142	0.154	1	0.81	0.773	0.637	-0.095	-0.032
Spread (AA)	0.052	0.267	0.311	0.277	0.242	0.81	1	0.965	0.819	-0.216	-0.08
Spread (A)	0.039	0.284	0.33	0.296	0.252	0.773	0.965	1	0.884	-0.303	-0.179
Spread (BBB)	-0.112	0.253	0.368	0.293	0.231	0.637	0.819	0.884	1	-0.438	-0.342
Stocks	0.135	-0.174	-0.243	-0.21	-0.147	-0.095	-0.216	-0.303	-0.438	1	0.663
Real Estate	0.274	-0.203	-0.27	-0.196	-0.141	-0.032	-0.08	-0.179	-0.342	0.663	1

Figure IA.5. Financial Market Dynamics: Historical and Simulated.
The figures depicts one exemplary simulated path and the 25th / 75th percentiles of simulated 10-year German government bond rates, AAA corporate bond rates, and the European stock market index from year 0 on. Prior to year 0, we show the actual historical evolution, up to year 0, which corresponds to 2015. Figure (a) is based on all simulated paths and Figure (b) is based only on those with the 5% largest average increase in the 10-year German government bond rate.

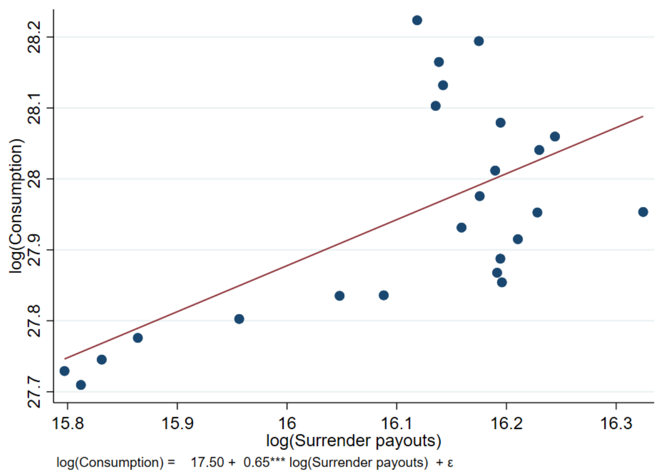


(a) All Paths.

(b) Paths with Rising Interest Rates.

E Surrender Payouts and Consumption

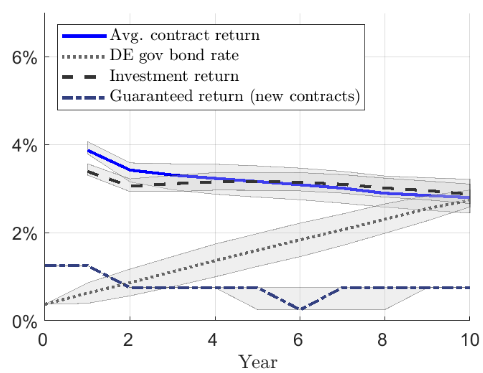
Figure IA.6. Correlation Between Surrender Payouts and Private Consumption.
The figure plots the logarithm of annual aggregate surrender payouts (x-axis) and the logarithm of total private consumption expenditures (y-axis) in Germany from 1996 to 2019 as scatter points. A univariate regression implies that consumption expenditures increase by 0.65% when surrender payouts rise by 1%. *Sources: BaFin (surrender payouts), OECD (private consumption expenditures).*



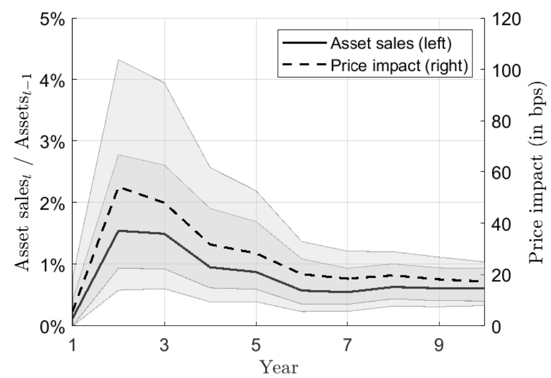
F Additional Simulation Results

Figure IA.7. Counterfactual Calibration: Returns, Asset Sales, Price Impact with Dynamic Investment Strategy.

Figure (a) depicts the simulated contract return for an average cohort, 10-year German government bond rate, the insurer's investment return, and the guaranteed return for new contracts assuming that the insurer follows the dynamic investment strategy. Figure (b) depicts the insurer's asset sales relative to the previous year's total assets (left axis) and the average price impact (right axis) assuming that the insurer follows a dynamic investment strategy. The average price impact is calculated as the price impact per EUR 1 sold, defined as the average asset class-specific price impact, as in Equation (10), weighted by the asset class-specific volume of sales. The figures show the median and 25th/75th percentile for each year.



(a) Interest rate and returns.



(b) Asset sales and price impact.

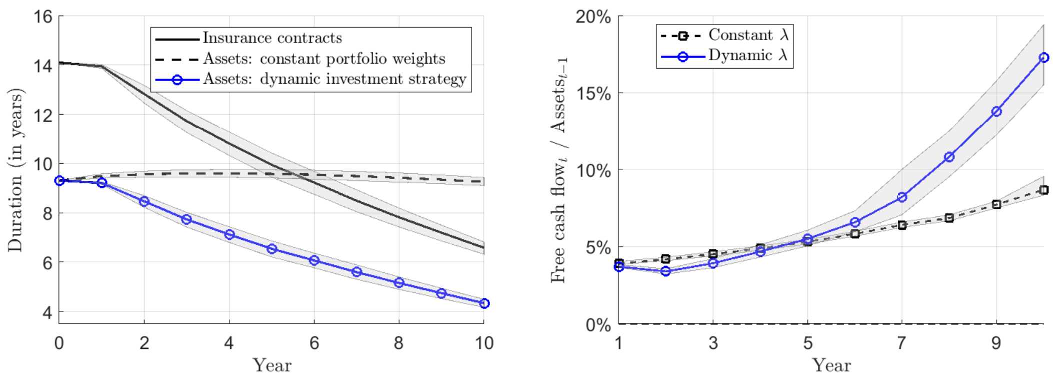
F.1 Counterfactual Calibration: Market Value Adjustments

An important driver for interest-rate-driven surrenders is that the surrender value is guaranteed ex ante, i.e., independent of short-term fluctuations in interest rates. Market value adjustments (MVAs), commonly found in U.S. deferred multiyear annuities (see Internet Appendix A), adjust surrender values for interest rate changes: an increase in interest rates reduces market-value-adjusted surrender values, everything else being equal.

We implement an MVA to examine how it affects surrender rates and asset sales. For this purpose, we use the same initial balance sheet calibration as in the baseline analysis but assume that, starting at $t = 0$, all cohorts' surrender values are subject to an MVA. The

Figure IA.8. Counterfactual Calibration: Duration and Free Cash Flow with Dynamic Investment Strategy.

Figure (a) depicts the modified duration of the insurer's insurance contracts (solid line), of the insurer's fixed-income investments assuming constant asset portfolio weights (dashed line), and of the insurer's fixed-income investments assuming a dynamic investment strategy (circles). The insurance contract duration does not differ with the investment strategy. Figure (b) depicts the insurer's free cash flow relative to the previous year's total assets in case of a constant surrender rate (squares) and in case of a dynamic surrender rate (circles) assuming that the insurer follows the dynamic investment strategy. We show the median and 25th / 75th percentiles in each year.



(a) Duration. (b) Free Cash Flow.

market-value-adjusted surrender value at year-begin $t, t \geq 1$, is $sv^h_{t-1,MVA} = (1 - mva^h_{t-1}) \cdot \vartheta \cdot v^h_{t-1}$, where mva^h_{t-1} is the MVA factor. Whereas an MVA may be implemented in various ways, we base the definition of the MVA factor on that most commonly found in the U.S.:

$$mva^h_{t-1} = 1 - \min\left\{\left(\frac{1 + \tilde{r}^h_{P,t-1}}{1 + \ell + r_{f,t-1,T^h-(t-1)}}\right)^{T-(t-1)}, \vartheta^{-1}\right\}. \tag{IA.9}$$

If $mva^h_{t-1} = 0$, then there is no MVA, and the policyholder receives the cash value less the surrender penalty. The larger mva^h_{t-1}, the smaller is the surrender payout. The minimum operator ensures that the MVA cannot overcompensate the surrender penalty, i.e., policyholders cannot receive more than the contract's cash value. ℓ adjusts the average level of mva^h_{t-1}, accounting for the spread on top of the risk-free rate earned by insurers. A low value of ℓ translates into a low average MVA factor, boosting surrender rates. We use $\ell = 0.015$, which makes the initial average level of the surrender rate in our model comparable to that in the baseline calibration.

Figure IA.9. Counterfactual Calibration: Market Value Adjustment Factor.

The figure depicts the market value adjustment factor, as defined in Equation (12). The figure shows the median and 25th/75th percentile for each year.

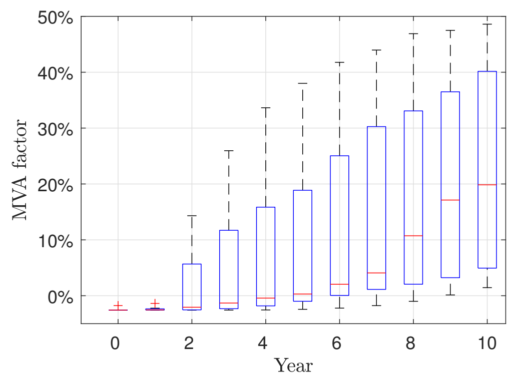
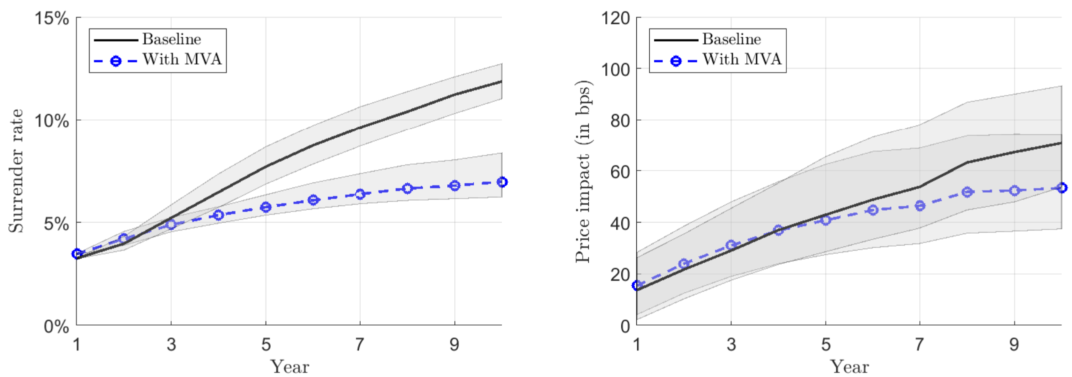


Figure IA.10 (a) compares the surrender rate in the counterfactual calibration with MVA to that in the baseline calibration. The MVA clearly reduces the surrender rate starting in year 4, after which it stabilizes close to 7%. In the first three years of the model, the surrender rate increases at a similar pace in both calibrations. During this time, MVA factors are not sufficiently large to offset strengthened surrender incentives since the minimum MVA factor is binding for most contracts due to low interest rates.

The relatively lower surrender rate translates into a lower volume of asset sales and lower price impact. The peak price impact is roughly 25% lower, namely 53 bps with MVA rather than 71 bps in the baseline calibration (see Figure IA.10 a). Taking into account that portfolio reallocation results in a peak price impact of 34 bps when surrender rates are constant, the MVA reduces the (remaining) surrender-induced price impact by almost 50%, specifically from 37 bps to 19 bps. These results show that an MVA can significantly reduce the interest rate sensitivity of surrender rates and, thereby, the price pressure resulting from interest-rate-driven surrenders.

Figure IA.10. Counterfactual Calibration: Market Value Adjustment.

Figure (a) compares the insurer's surrender rate in a counterfactual calibration with market value adjustments (MVAs) to that in the baseline calibration. Figure (b) compares the insurer's price impact in a counterfactual calibration with MVAs to that in the baseline calibration. Both figures show the median and 25th/75th percentile for each year.



(a) Surrender Rate.

(b) Price Impact.

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