Life Insurance Convexity*

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Abstract

Life insurers massively sell savings contracts with surrender options which allow policyholders to withdraw a guaranteed amount before maturity. These move toward the money when interest rates rise. Using data on German life insurers, we estimate that a 1ppt increase in interest rates raises surrender rates by 17bps. We quantify the resulting liquidity risk in a calibrated model of surrender decisions and insurance cash flows. Simulations predict that surrender options can force insurers to sell up to 3% of assets, depressing asset prices by 90bps. This effect is amplified by insurers' long-dated investments and it concentrates on long-term assets when insurers follow a duration matching investment strategy.

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"[...] 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."[1]

Life insurers are significant financial intermediaries as they hold 10% of global financial assets (IMF, 2016). Life insurance contracts financially protect policyholders against mortality and longevity risks, accounting for more than 20% of households' assets.[2] Annuities, facilitating retirement saving, represent the majority of life insurers' business. These contracts usually entail a surrender option, which allows policyholders to terminate a contract before its maturity and receive an ex-ante guaranteed surrender value. When interest rates rise, this surrender option becomes more valuable. This paper aims to estimate the liquidity risk and financial market spillovers resulting from an interest rate-driven increase in surrender activity.

First, we provide empirical evidence for a causal effect of interest rates on life insurance surrender. Our estimate implies that a 1ppt increase in interest rates leads to 17bps increase in surrender rates, i.e., in the share of life insurance contracts surrendered. Thus, the interest rate duration of life insurance contracts decreases with interest rates, a characteristic of fixed income products often called *convexity*. Second, we estimate a structural model for policyholders' surrender decisions and embed this into a calibrated, granular simulation model with a stochastic financial market and representative life insurer's cash flows and balance sheet. Simulations predict that increased surrender rates during an interest rate rise of roughly 25bps per year would force insurers to sell up to 3% of their assets annually. Under reasonable assumptions about insurers' price impact, our results suggest that surrender-driven asset sales would significantly reduce asset prices, by up to 90bps. Third, we use our model to explore counterfactual calibrations. We find that forced asset sales are primarily driven by the duration of insurers' assets, which boosts the value of surrender options when interest rates rise. Insurers' investment strategy has little effect on the volume of asset sales but a strong effect on their timing, as they prepone asset sales, as well as on their composition, affecting relative asset prices across maturities.

There is increasing concern about the liquidity risk implied by surrender options, which is amplified by the indication of central banks to taper asset purchases (e.g., Cancryn, Adam, 2015; ESRB, 2015; ECB, 2017; Deutsche Bundesbank, 2018; ESRB, 2020; IMF, 2021). For example, the European Insurance and Occupational Pension Authority (EIOPA) has included a combined increase in surrender rates and interest rates in their 2018 stress test.[3] Indeed, total surrender payments are economically significant. For example, European life insurers paid out EUR 362

[1] Introductory statement by Mario Draghi, hearing before the committee on economic and monetary affairs of the European parliament, 26 November 2018.

[2] Life insurance and annuities (including trusts) 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 40% of European households' assets (ECB, 2021).

[3] Results of the 2018 EIOPA stress test are published at `https://www.eiopa.europa.eu/insurance-stress-test-2018_en`. Similarly, the U.S. National Association of Insurance Commissioners (NAIC) has proposed a liquidity stress tests for U.S. life insurers (see NAIC, 2021).

billion for surrendered contracts in 2019, which corresponds to more than 40% of their net premium income (EIOPA, 2020).[4] However, little is known about the economic significance of surrender rates on life insurers' liquidity and their interaction with interest rates.

We address this gap by using the German life insurance market as a laboratory. German life insurers collect EUR 150 billion annually in insurance premiums (EIOPA, 2020). The most popular life insurance contracts in Germany are participating policies, whose cash an insurer invests into a single portfolio of assets. These contracts make up more than 85% of German life insurance reserves (EIOPA, 2020) and include surrender options with ex-ante guaranteed surrender values by default. When rising interest rates depress asset prices, surrender becomes more attractive as it allows policyholders to exchange the claim on insurers' assets for the guaranteed surrender value. To empirically explore this channel, we combine printed and digital records of the German financial supervisory authority BaFin to construct a panel of annual surrender rates covering all German life insurers since 1996. The main explanatory variable is the 10-year German government bond rate, which is a common benchmark rate for long-term financial products.

The OLS estimate implies that a 1ppt increase in interest rates associates with a 17bps increase in the surrender rate, controlling for time-invariant heterogeneity across insurers, macroeconomic conditions, and the composition of life insurance business. The economic magnitude is large: a 1 standard deviation increase in interest rates roughly corresponds to an aggregate increase in surrender payouts by EUR 1.6 billion. To zoom in on the economic mechanism behind this correlation, we explore the interaction between interest rates and the guaranteed minimum return on life insurance contracts. The larger the guaranteed return, the smaller is the surrender option value's sensitivity to interest rates. Consistently, we document that the correlation between surrender rates and interest rates is weaker when the guaranteed return for new life insurance contracts is larger and that this interaction effect is significantly stronger for insurers with more new insurance business.[5] Comparing the sensitivity across insurers allows us to include time fixed effects, which absorb any aggregate shocks that might correlate with both interest and surrender rates, such as insurers' investment strategy.

To further strengthen the identification, we exploit the U.S. federal funds rate, which reflects the Fed's monetary policy stance, as an instrumental variable for German government bond rates. We find that the federal funds rate is significantly positively correlated with the German government bond rate, consistent with an international bond market channel. Yet, German life insurers hold very little U.S. treasuries, suggesting that there is the effect of the German life insurance market on U.S. monetary policy is negligible, which supports the exclusion restriction. Using this alternative identification strategy has a modest impact on the coefficients and their significance, suggesting a causal effect of interest rates on surrender rates.

Motivated by this evidence, the second part of this paper quantifies the risk of surrender-driven

[4] Similarly, U.S. life insurers paid out $345 billion, which corresponds to more than 40% of their net premium income (NAIC, 2020a).

[5] Due to data limitations, we only observe the guaranteed rate for new insurance contracts, which applies to all insurers, but not the insurer-specific guaranteed rate of all existing contracts.

asset sales. For this purpose, we estimate a structural model of policyholders' surrender decisions, which we embed in a detailed, calibrated simulation model with a dynamic, stochastic financial market and a representative life insurer's cash flows and balance sheet. The calibration captures the characteristics of insurers' legacy assets, including their composition and duration, as well as legacy insurance contracts, which is important to appropriately capture cash flow dynamics. The financial market model combines a stochastic short rate model, based on Vasicek (1977), with models for bond spreads other other investments, and takes into account the correlations across asset classes.

We simulate paths with a length of 10 years, among which we select the 5% with the strongest interest rate rise. Among these "stress" paths, the average annual interest rate change is roughly 25bps, which corresponds to the 75th percentile of annual changes in the 10-year German government bond rate since 1980. This interest rate rise boosts surrender rates to roughly 20% in our simulation. The model predicts that surrender payments would drain the life insurer's free cash flow and, after four years, would force the insurer to sell assets. The longer the interest rate rise lasts, the more assets the insurer has to sell each year, with up to 3% of total assets after 10 years of rising interest rates. Due to the systematic nature of an interest rate rise, the effects are plausibly similar across life insurers that offer similar contracts.

To provide an estimate for aggregate asset sales, we scale our simulations to the aggregate size of European life insurers that offer similar contracts with surrender options. Building on estimates for insurers' price impact from previous literature, the simulations imply that surrender-driven asset sales reduce asset prices by up to 90bps. This magnitude is plausible compared to other studies on fire sales by insurers and economically significant, especially in the bond market, which is the center of insurers' investment activity.[6] The significant financial market impact implied by our results provides a potential rationale for policymakers' effort to pay more attention to the provision of surrender options, which we discuss in detail.

In counterfactual calibrations, we explore the sensitivity of our results. We find that an important determinant is the duration of the insurer's asset investments. The longer the asset duration, the slower is the reaction of life insurance contract returns to rising market interest rates and, thus, the stronger are surrender incentives. An increase in asset duration from below 8 to above 12 years years relates to an increase in asset sales from below 1% to more than 3% in an average year.

In our baseline model specification, we assume that the insurer in our model keeps constant the portfolio weights across asset with different duration. However, when rising interest rates reduce the duration of insurance contracts, insurers are likely to match this dynamic by reducing their asset duration (Domanski et al., 2015). Following this rationale, we implement a sensitivity analysis with an dynamic adjustment of asset duration to the duration of insurance contracts. A lower asset duration strengthens the pass-through of interest rate changes on contract returns and, thereby, weakens surrender incentives. Consistently, we find that surrender rates are smaller with

[6]For example, Liu et al. (2021) and Kubitza (2021) provide empirical evidence that a bond price impact of 1% and below can affect the financing and investment behavior of municipalities and non-financial firms, respectively.

a dynamic investment strategy. However, this investment strategy itself motivates the insurer to sell a large fraction of their long-term assets when interest rates rise in order to reduce the overall asset duration. As a result, the total asset sales and price impact are similar to the situation with constant portfolio weights. Nonetheless, the composition of asset sales changes. In the baseline specification, the insurer sells mostly short-term assets in order to keep constant portfolio weights across assets, since these gain in value relative to long-term assets when interest rates rise. With a dynamic investment strategy, the insurer sells mostly long-term assets in order to reduce the overall asset duration. This has important consequences for the slope of the yield curve. With constant portfolio weights, surrender-driven asset sales increase *short-term* relative to long-term yields, which flattens the yield curve. When matching asset and liability duration, surrender-driven asset sales increase *long-term* relative to short-term yields, which steepens the yield curve.

Liquidity risk has been long acknowledged as an important driver of fragility in the financial sector. The previous literature has mostly focused on banks (starting with Diamond and Dybvig, 1982) and, more recently, on mutual funds (e.g., Coval and Stafford, 2007). Life insurance companies massively sell contracts with surrender options that resemble the withdrawal option of demand-deposit contracts, yet life insurers significantly differ from other financial institutions such as banks by offering particularly long-term guarantees (Koijen and Yogo, 2021; Ellul et al., 2020), managing reserves to facilitate risk sharing across generations (Hombert and Lyonnet, 2019; Hombert et al., 2021), and being at the center of fixed income markets (Ellul et al., 2011; Kubitza, 2021; Liu et al., 2021). Whereas a growing literature studies how regulatory frictions affect insurers' investment behavior and funding structure (Becker and Ivashina, 2015; Koijen and Yogo, 2016; Sen, 2020; Becker et al., 2021), little is known about life insurers' liquidity risk.[7]

In theory, the surrender option value increases with interest rates (Albizzati and Geman, 1994; Förstemann, 2019; Chang and Schmeiser, 2020). We provide empirical evidence that this economic channel generates a causal effect of interest rates on surrender rates, extending previous studies that document a positive correlation between interest and surrender rates (Dar and Dodds, 1989; Kuo et al., 2003; Kiesenbauer, 2012; Eling and Kiesenbauer, 2014). In a one-period model, Förstemann (2019) highlights the potential asset sales resulting from all policyholders surrendering after a sufficiently large and immediate hike in interest rates that endangers insurers' solvency. Extending these studies, we provide an empirically calibrated model and estimate the effect of more plausible increases in interest rates, taking into account policyholders' empirically observed surrender behavior and the dynamics of insurers' balance sheet and cash flows.

The convexity of life insurance is important for understanding life insurance markets as it provides a possible explanation for why life insurers maintain large negative duration gaps in practice, i.e., longer-dated liabilities than assets (e.g., IMF, 2017).[8] When interest rates rise,

[7]Whereas surrender options expose life insurers to liquidity risk, life insurers may profit from policyholders' behavioral biases regarding their need to surrender a contract (Gottlieb and Smetters, 2021). Consistent with this rationale, our simulations suggest a modest impact of an increase in surrender rates on life insurers' profitability.

[8]Koijen and Yogo (2021) discuss other potential explanations for why life insurers maintain negative duration gaps.

negative duration gaps effectively hedge life insurers against interest rate risk. It is, thus, important for regulation to take convexity into account.

The convexity imposed by surrender options resembles the convexity resulting from prepayment options in fixed-rate mortgages. In this case, an increase in (long-term) interest rates makes prepayment less favorable and, thereby, increases the duration of mortgage-backed securities, amplifying interest rate volatility (Hanson, 2014).

Our results emphasize the role of insurers' long-dated asset investments in amplifying surrender-driven liquidity risk by widening the gap between guaranteed surrender value and the value of insurers' investments when interest rates rise. This insight contrasts previous literature, that has highlighted the positive role of long-dated asset investment in facilitating inter-cohort risk sharing (Hombert and Lyonnet, 2019; Hombert et al., 2021) and riding out short-term market fluctuations (Timmer, 2018; Chodorow-Reich et al., 2020).

This paper also contributes to studies on financial intermediaries' price impact. A growing literature empirically documents that insurers and, more generally, institutional investors significantly affect asset prices (e.g., Ellul et al., 2011, 2015; Greenwood and Vissing-Jorgensen, 2018; Koijen and Yogo, 2019; Girardi et al., 2021; Kubitza, 2021; Liu et al., 2021). In the calibrated models of Greenwood et al. (2015) and Ellul et al. (2020), fire sales result from banks' and insurers' desire to replenish capital ratios by de-leveraging and de-risking after an exogenous income shock, respectively. Our model complements Ellul et al. (2020)'s model in particular, in which life insurers de-risk by selling illiquid bonds and, thereby, reduce capital requirements. In contrast, asset sales are directly forced by surrendering policyholders in our model.

The remainder of this paper proceeds as follows. Section 1 provides an overview of the institutional background and documents the economic significance of surrender options for life insurers' cash flows. In Section 2 we provide empirical evidence that interest rates increase surrender rates. 3 presents our model and quantifies surrender-driven asset sales and price impact. Section 4 discusses empirical predictions and policy implications, and Section 5 concludes.

1 Institutional Background and Anecdotal Evidence

1.1 Life Insurance Contracts and Surrender Options

The majority of life insurers' business comprises savings contracts, which policyholders can convert into a lump sum payment or a stream of annuity payments at retirement. Before retirement, policyholders pay premiums, typically annually, which are invested by the insurer. Most life insurance contracts in Europe, and especially in Germany, are participating contracts, which means that the insurer pools premiums and invests in a common asset portfolio.[9]

[9] More than 60% of European life insurance reserves and nearly 90% of German life insurance reserves attribute to are participating contracts (EIOPA, 2020). Savings contracts also dominate the U.S. life insurance business but with a stronger focus on non-participating policies that allow policyholders to choose the investment strategy (Koijen and Yogo, 2021). These often include guaranteed surrender values as well, as we discuss in Appendix A.

88% of European life insurance contracts include surrender options (EIOPA, 2019). Almost all participating contracts with surrender option (91%) also include an ex-ante guaranteed surrender value (EIOPA, 2019). Guaranteed surrender values are less common for unit-linked contracts (23%), consistent with policyholders bearing more investment risk. Due to the prevalence of participating contracts in Europe, the overall share of contracts with both surrender option and guaranteed surrender value is substantial, corresponding to roughly EUR 4.5 trillion (60%) of European life insurance reserves (EIOPA, 2020).

Disincentives to surrender result from penalties imposed by insurers and potentially lost tax advantages. 27% of European life insurance contracts carry a tax disincentive to surrender and 17% a surrender penalty (EIOPA, 2019). According to anecdotal information from the German insurance industry, surrender penalties are extremely small (in the order of 2.5% of surrender values) since they are supposed to cover only administrative expenses arising from surrender activity. In our model, we explicitly include surrender penalties, while tax disincentives are implicitly considered in the empirical calibration.

In Europe, Germany is among the countries with the highest prevalence of surrender options and guaranteed surrender values (EIOPA, 2019). The guaranteed surrender value of German participating contracts is mandated to correspond to the previous year's accumulated cash value (i.e., the realized savings) less administrative costs (see German insurance contract law, Section 169). Since insurers guarantee a minimum annual return on policyholders' savings, surrender values are bounded from below. These policy characteristics are similar in other countries, such as the U.S. (see Appendix A).

1.2 Economic Significance of Surrender Options

We explore the size of surrender payments by life insurers drawing on data retrieved from EIOPA (2020) and the NAIC (2020a) about life insurers' cash flow and assets at the country level. In total, surrender payments in 2019 were EUR 362 billion in Europe, thereof EUR 21.5 billion in Germany, and EUR 308 billion in the U.S. (equivalently, $345 billion). Surrender payments correspond to 44% of total life insurance payouts in both Europe and in the U.S. and, thus, comprise almost half of insurers' cash outflows.

In comparison to cash inflows, we find that surrender payments correspond to a similar share of life insurance premiums. Also when accounting for other cash flows, from investment income and due to insurance benefits and expenses, surrender payments remain a significant share of the resulting net cash flow, for example, 24% in Germany (BaFin, 2019). We conclude that surrender payments are a significant determinant of life insurers' liquidity.

There is sizable variation in the relative size of surrender payments across countries, as we show in Figure 1. An important determinant for this variation is the type of insurance contracts: we find that variation in the share of non-participating contracts (relative to all life insurance reserves) explains 27% of the variation in surrender payments relative to premiums across EU countries in 2019 (the correlation is 52%). Thus, although non-participating contracts often do not guarantee surrender values, this finding suggests they are surrendered relatively often. Other potential determinants of country-level variation in surrender rates are institutional characteristics of the insurance sector, tax systems, and the macroeconomic environment.

To pay out surrender values, life insurers might need to sell assets. Life insurers traditionally invest in long-term and relatively illiquid assets, facilitated by the long maturity of life insurance contracts (EIOPA, 2017a; NAIC, 2020b; Chodorow-Reich et al., 2020). We estimate that roughly 42% of European life insurers' assets are liquid, with wide variation ranging from 20% (Germany) to 85% (Hungary).[10] Surrender payments correspond to approximately 15% of these liquid assets. Thus, the size of surrender payments is economically significant, not only relative to insurers' cash flows but also relative to their liquid asset holdings.

1.3 Anecdotal Evidence and Insurance Runs

Anecdotal evidence emphasizes the link between interest rates, surrender, and life insurer liquidity, highlighting it's economic importance. For example, U.S. surrender rates spiked in response to a sharp interest rate rise in the late 1970s and early 1980s, from roughly 3% in 1951 to 12% in 1985 (Kuo et al., 2003). As a consequence, U.S. life insurers liquidated a large share of their investments (Russell et al., 2013).

In the most extreme case, a mass exercise of surrender options can result in an *insurance run*, endangering insurers' financial health. In the early 1990s, asset illiquidity of several U.S. life insurers resulted in insurance runs and lead to the failure of seven life insurers (Brennan et al., 2013). For instance, Executive Life Insurance Company and First Capital Holding Corp. invested a large share of assets in illiquid junk bonds and securities (DeAngelo et al., 1994; Jackson and Symons, 1999), and Mutual Life Insurance Company of New York had large real estate exposures. Notably, these runs were amplified by policyholders holding Guaranteed Investment Contracts (GICs), which are savings contracts with financial guarantees (Brewer and Strahan, 1993; Ho, 2004), resembling the modern savings contracts we examine in this paper. Again, in 1999, rising interest rates sparked an *insurance run* on GICs of General American, a U.S. life insurer, resulting in its failure (Fabozzi, 2000; Brennan et al., 2013).

Rising interest rates also triggered a run-like situation in the South Korean life insurance market in 1997-98. As interest rates sharply increased (by roughly 4ppt 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 roughly one third of Korean life insurers exited the market (Geneva Association, 2012).

[10] We calculate the sum of life insurers' holdings of cash and deposits, common equity, equity and money market mutual funds, and central government, treasury, and central bank bonds according to EIOPA (2020) in 2019. We include assets hold for unit- or index linked insurance, because they are included in the total surrender amount. Examples for illiquid assets are loans, real estate, and corporate bonds.

2 Empirical Analysis

In this section, we provide empirical evidence that market interest rates boost life insurance surrender rates, consistent with policyholders maximizing yield.

2.1 Data and Empirical Specification

We use the German life insurance market as an empirical laboratory. In Germany, life insurance is in general very popular and life insurance demand is comparable to other developed countries.[11] Within the German life insurance market, savings contracts with guaranteed surrender values are particularly popular, as we document in the previous section.

The German financial supervisory authority *BaFin* annually publishes information about surrender rates, premium income, investment return, and portfolio size for each German life insurer (excluding reinsurers), called *Erstversichererstatistik* (i.e., *statistics on primary insurers*). We digitize the data for 1995 to 2010, which is available only in print (in the German national library) or pdf format (at `www.bafin.de`). Since a common identifier of insurers is missing in the data, we match insurers by hand over time, which results in a survivorship-bias-free panel from 1995 to 2019.[12] The panel structure allows us to include insurer fixed effects in regressions, controlling for time-invariant insurer characteristics.

The dependent variable in our analysis is an insurer's annual surrender rate, which is the share of contracts surrendered weighted by insurance in force.[13] Before 2016, BaFin reports two surrender rates: an early surrender rate (surrender rate of new business) and a late surrender rate (other surrender as a share of the average contract portfolio in a given year). Instead, starting in 2016, BaFin reports an overall surrender rate. In our baseline analysis, we focus on the overall surrender rate. For this purpose, we compute the overall surrender rate for years earlier than 2016 as the weighted average of the early and late surrender rate, using the previous year's insurance in force.[14] Therefore, our final sample starts in 1996. All insurer-level variables are winsorized at the 1% and 99% levels. In an average year, the sample comprises 93 life insurers, with EUR 2.3 trillion of life insurance business in force and EUR 218 billion of new business. The number of insurers, premiums and volume of new business is relatively stable over time, whereas the volume of insurance in force

[11] For example, life insurance premiums per capita (as percentage of GDP) were \$1,161 (2.41%) in Germany, \$1,978 (4.6%) in advanced European and Middle East Asia, and \$1,774 (2.91%) in North America in 2019 (Swiss Re Institute, 2019).

[12] We translate values from German currency ("Deutsche Mark") to Euro for years 1995 to 2000 using the official exchange rate 1 EUR = 1.95583 Deutsche Mark.

[13] The level of insurance in force is computed as the final payout at contract maturity assuming that the current cash value and future premiums grow at the minimum guaranteed return in future years.

[14] Specifically, we follow BaFin's definition of the overall surrender rate and compute it for years $t \leq 2015$ as

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

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 early and late surrender rate, respectively.

is increasing, which jointly suggests that the duration of insurance contracts increases as well (see Figure 2).

The average surrender rate is 4.9% 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 surrender rate is on average smaller than that the withdrawal rate of time deposits. For example, in a sample of Greek deposit accounts, Artavanis et al. (2019) document that, in calm times, 15% of time deposits are annually withdrawn before maturity, on average.

The main explanatory variable is the level of market interest rates. We use the annualized yield on German government bonds with a residual maturity of 10 years since it is a widely used benchmark and available with long history.[15] The 10-year German government bond rate varies significantly during the sample horizon 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

$$\text{Surrender rate}_{i,t} = \alpha \cdot \text{Interest rate}_t + \beta \cdot X_{i,t-1} + \gamma \cdot Y_{t-1} + u_i + \varepsilon_{i,t}, \tag{1}$$

where Interest rate_t is the 10-year German government bond rate, $X_{i,t-1}$ are insurer control variables, Y_{t-1} macroeconomic control variables, and u_i are insurer fixed effects. α estimates the effect of interest rates on surrender rates. We expect that $\alpha > 0$, consistent with an increase in the value of surrender options when interest rates rise. Consistent with this assumption and the model specification, Figure 2 (b) suggests a linear relation between surrender rates and interest rates.

To control for a potential impact of the composition of an insurer's contract portfolio on surrender rates, $X_{i,t-1}$ includes the lagged share of new insurance business (relative to insurance in force at year-end) at the insurer level. Moreover, we control for an insurer's lagged investment return, capturing potential performance-driven surrender incentives. On average, 12% of insurance in force is new business and the investment return is 5% (Table 1).

Since the explanatory variable is at the year level, we cannot include year fixed effects in the baseline regression. Instead, we control for a wide range of macroeconomic characteristics that potentially affect surrender rates. In particular, we control for lagged inflation (retrieved from the BIS), GDP growth and investment growth (retrieved from the OECD), and a banking crisis dummy for Germany (provided by Laeven and Valencia, 2018). Moreover, we include information from the German Insurance Association (GDV) on the lagged aggregate German life insurance business, namely the log of total new life insurance contracts, capturing variation in insurance demand, and the share of new term life contracts, capturing variation in the composition of life insurance business.

In additional specifications, we interact the German government bond rate with insurer and macro characteristics, which allows us to additionally include year fixed effects. For this purpose, we use the guaranteed minimum contract return ("Guaranteed return") for new insurance business, re-

[15] Our results are robust toward using other maturities, e.g., 20 years. We retrieve end-of-month yields from the German Bundesbank and take annual averages.

flected by the technical discount rate for German life insurance contracts ("Höchstrechnungszins").[16]

Despite controlling for a wide array of control variables, there are two important concerns regarding the identification of α in Equation (1). First, unobserved variation in the German economic environment can affect both interest rates and surrender rates. Second, by affecting life insurers' liquidity, an increase in surrender rates can affect life insurers' investment behavior and, thereby, interest rates. Indeed, German life insurers hold roughly 6% of outstanding German government debt securities.[17] On the one hand, we address this concern by including fixed effects in interaction models, which control for aggregate bond demand. On the other hand, we push causal identification by using the U.S. federal funds rate, reflecting variation in U.S. monetary policy, as an instrumental variable for German government bond rates.

The first stage of our regressions shows that the federal funds rate is a relevant instrument since it significantly and positively correlates with German government bond rates. Intuitively, tighter U.S. monetary policy (i.e., an increase in the federal funds rate) raises U.S. treasury rates, which affects German government bond rates through an international arbitrage channel. Consistent with the argument, the results are similar when using the U.S. treasury rate instead of the federal funds rate as an instrument (see Appendix B). F statistic is well above the critical value of 10, alleviating the concern that the instrument is weak. The exclusion restriction requires German surrender rates to be orthogonal to U.S. monetary policy holding German government bond rates fixed. First, German life insurers only hold a negligible share of outstanding U.S. treasuries.[18] Thus, (the fear of) potential bond sales by German life insurers are unlikely to affect U.S. monetary policy. Second, in Appendix B, we show that neither the U.S. federal funds rate nor the U.S. treasury rate significantly correlates with surrender rates when controlling for the German government bond rate. Third, to alleviate the concern that international macroeconomic trends might affect both U.S. monetary policy and German surrender rates, we include a large set of control variables for the German economy.

2.2 Results

Consistent with the hypothesis that higher interest rates boost surrender rates, in Table 2 we document a highly significant and positive correlation between surrender rates and the 10-year German government bond rate (column 1). A one-standard deviation increase in the interest rate relates to an increase in the surrender rate by roughly 0.13 standard deviations (32.9bps). A simple back-of-the-envelope-calculation shows that this magnitude is economically significant: it corresponds to an increase by roughly EUR 1.6 billion in total surrender payments in Germany,

[16] See Eling and Holder (2012) for a discussion on the relation between technical discount rate and guaranteed minimum contract return.

[17] Outstanding German government debt securities are EUR 1,509 billion as of 2018 (Source: *ECB Statistical Data Warehouse*). German life insurers' total holdings of German government bonds are EUR 89.5 billion as of 2018 (Source: EIOPA (2020)).

[18] German life insurers hold EUR 723.8 million in U.S. treasuries as of 2018 (Source: EIOPA (2020)), compared to EUR 10,789 billion of 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"*).

using German life insurance in force reported by BaFin (2019) for 2019 as a benchmark.[19]

To explore the economic channel behind the correlation of surrender rates with interest rates, we examine the interaction with the guaranteed minimum return of insurance contracts. If policyholders maximize yield, a higher guaranteed return will reduce their sensitivity toward interest rates, consistent with our model (see Section 3.1). Since we only observe guaranteed return for new insurance contracts, in column (2) we focus on insurers with a large share of new insurance business. Consistent with the hypothesis of yield-maximizing policyholders, we find a large and significantly negative coefficient on the interaction between interest rates and guaranteed return. The estimate suggests that a guaranteed return of 3% would be necessary to make policyholders completely insensitive to interest rate changes, which is relatively large compared to historical levels of guaranteed returns.

Since the guaranteed return applies to new insurance contracts, its effect on surrender rates' interest-rate sensitivity should be particularly strong for insurers with a large share of new business. To test this hypothesis, we include a triple-interaction term of interest rates, the guaranteed return, and an insures' share of new business. Importantly, this specification allows us to include not only insurer but also year fixed effects, which alleviates the concern that unobserved aggregate changes, e.g., in insurance regulation or the macroeconomic environment, affect both interest and surrender rates as well as the guaranteed return. 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) re-estimate the previous specifications using the U.S. federal funds rate as an instrument for the 10-year German government bond rate. This alternative identification strategy has a modest impact on the estimated coefficients and their significance and, thereby, provides strong evidence for a causal effect of interest rates on surrender rates.

We provide additional results in Appendix B. First, we show that the estimated coefficient is also similar when using the 10-year U.S. treasury rate as an alternative instrument, consistent with the argument that changes in the U.S. federal funds rate transmit to German government bond rates through an international bond market channel. Second, we document that the coefficient on the U.S. federal funds rate becomes highly insignificant once controlling for the 10-year German government bonds rate, which supports the identifying assumption that there is no alternative channel through which the U.S. federal funds rate affects German surrender rates.

Whereas our model focuses on rising interest rates, these are, on average, declining in the sample. At the margin, it seems reasonable to assume that the effects of an interest rate rise and decline on surrender rates are similar. To provide further evidence, we interact the interest rate in our baseline specification (1) with a dummy variable indicating declining interest rates. We find

[19]The ratio of aggregate surrender payments to aggregate volume surrendered in German life insurance ranges from 14.1% to 17%, with an average of 15.5% according to BaFin's *Erstversichererstatistik* from 2011 to 2019. Using the total volume of insurance in force in Germany at year-begin 2019 (EUR 3 126 billion), a 1ppt increase in the surrender rate roughly corresponds to $0.00329 \times 3\ 126 \times 0.155$ = EUR 1.6 billion.

that the coefficient on the interaction is small in magnitude and insignificant, while the coefficient on the interest rate keeps a similar magnitude as in the baseline results (see Appendix B). This suggests that our baseline estimates apply to both rising and declining interest rates.

3 Surrender Options and Financial Fragility

In this section, we develop and apply a model to quantify the impact of surrender options on life insurer liquidity and financial markets.

3.1 Model

We first propose and estimate a structural model for surrender rates in life insurance. Second, we embed this model into a broader model 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.[20] Below we provide a broad overview of the model ingredients, and discuss more details in the Online Appendix D.

3.1.1 Savings Contracts. Our model picks up the main features of life insurance savings contracts. Specifically, contracts are long-term and they annually return the maximum of a (at contract begin) fixed guaranteed minimum return and the return on underlying asset investments. For tractability, we focus on contracts' savings phase. Policyholders annually invest a premium EUR P and receive a lump-sum payment at contract maturity.[21] Each year, each policyholder may surrender her contract, upon which the insurer pays out her contract's cash value, which is the contract return accumulated since contract begin, less a surrender penalty.

The total cash value of policyholder cohort h evolves according to

$$V_{t+1}^h = (1 - \lambda_{t+1}^h) \cdot (1 + \tilde{r}_{P,t+1}^h) \cdot V_t^h + N_{t+1}^h \cdot P, \tag{2}$$

where V_{t+1}^h is the cash value at year-end $t+1 > h$, $\tilde{r}_{P,t+1}^h$ the contract return credited at year-end $t+1$, P is the annual premium, N_{t+1}^h the number of policyholders at year-end $t+1$, and h the contract begin (identifying the policyholder cohort). At contract begin, $V_h^h = N_h^h \cdot P$. The cash value V_{t+1}^h corresponds to the account value of the insurer's contract liabilities following German historical cost accounting.

[20] Since interest rates were low in 2015, from the perspective of an insurer's balance sheet, this year represents a reasonable starting point to assess the effects of rising interest rates. Indeed, the Fed started to tighten monetary contract, in contrast, the ECB did not. We neither assess the likelihood nor adequacy of rising interest rates in 2015 from a macroeconomic perspective, which would exceed the scope of this paper.

[21] Many life insurance contracts also allow to transfer the lump-sum payment to an annuity contract, providing the policyholder with a pre-defined payment stream. Nonetheless, many studies find that policyholders rarely annuitize a large fraction of their wealth, which is often referred to as the *annuity puzzle* (see, e.g., Mitchell and Moore, 1998; Brown, 2001). A loss of protection against longevity risk provides an additional cost of surrendering an annuity, plausibly reducing interest rate-sensitivity of annuities. Since annuitants do not pay premiums, they have little impact on an insurer's liquidity. For these reasons, we do not expect our results to differ when including the annuity phase of contracts.

Policyholder dynamics are governed by the surrender rate λ_{t+1}^h, which is the share of previous year's policyholders N_t^h that surrender at year-begin $t+1$, and thus $N_{t+1}^h = (1-\lambda_{t+1}^h)\cdot N_t^h$. The surrender value of contracts in cohort h, SV_t^h, is paid out upon surrender in $t+1$. Following German insurance contract law (Section 169), it equals the lagged cash value V_t^h less a relative surrender penalty $1-\vartheta$, $\vartheta \in (0,1)$, such that $SV_t^h = \vartheta \cdot V_t^h$. At contract begin h, there is a fixed number of policyholders $N_h^h = N$, which is consistent with the historically very stable evolution of new insurance business (see Figure 2).[22] At contract maturity T^h, the final cash value $V_{T^h}^h$ is paid out to the remaining policyholders.

To model the dynamics of cash values, we are left with specifying the dynamics of the contract return and surrender rate. We endogenize the surrender rate in the next section. The annual contract return is given by

$$\tilde{r}_{P,t+1}^h = \max\{r_G^h,\, \tilde{r}_{t+1}^*\}. \tag{3}$$

Here, $\tilde{r}_{t+1}^*$ is the investment return allocated to policyholders. r_G^h is the minimum guaranteed rate of return, which is fixed at contract begin h for the entire contract life. Motivated by significant life insurer insolvencies in the 1980-90s regulators set (explicit and implicit) maximum levels for guaranteed returns which depend on long-term interest rate averages (Grosen and Jorgensen, 2002). Following German life insurance regulation, we assume that r_G^h is annually adjusted and tracks 60% of the 10-year moving average of 10-year German government bonds at time $t=h$ in 50bps steps (Eling and Holder, 2012).[23]

Due to their dominance in the European life insurance market (as described in Section 1), we focus on participating contracts, which means that premiums are invested at the life insurer's discretion.[24] Policyholders receive a fraction $\xi \in (0,1)$ of the insurer's total investment income R_{t+1}^{inv} allocated relative to cash values if this exceeds the guaranteed return,

$$\tilde{r}_{t+1}^* = \xi \frac{R_{t+1}^{inv}}{\sum_{h=1}^t V_t^h}. \tag{4}$$

The investment income R_{t+1}^{inv} includes fixed income coupon payments, stock dividends, and rents less depreciations on the insurer's GAAP (historical cost) balance sheet.[25] Therefore, it depends

[22] Since contract returns react to changes in interest rates with a considerable time lag, it seems plausible to assume that demand would decrease upon an interest rate rise, reducing the insurer's cash inflow. Following this argument, the assumption of a fixed number of new policyholders leads to plausibly conservative estimates. Moreover, time-varying demand is implicitly captured by policyholders' ability to surrender contracts in the first year after purchase.

[23] German law explicitly specified 60% of the 10-year yield on AAA-rated European government bonds as the cap of the guaranteed return until 2015 (§65 VAG). Since 2015 the calculation of the cap is not specified any more (§88 VAG). However, German regulators did not deviate much from the 60% rule. For example, our model predicts that the guaranteed return would be lowered in 2017, if interest rates were not increasing by much, which matches the German regulator's actual response.

[24] This form of delegated asset investment is common in many jurisdictions. Assets for participating contracts appear on the insurer's *general account*, while assets for non-participating (i.e., unit- or index-linked) contracts appear on the *separate account*. Separate accounts are relatively small, e.g., 10% of German life insurers' total assets (Source: *BaFin Erstversichererstatistik*).

[25] The investment income R_{t+1}^{inv} does not consider unrealized market value gains. We abstract from insurers' ability

on the allocation and evolution of insurers' investments, which we discuss in Section 3.1.3.

3.1.2 Surrender Decisions. Motivated by the empirical analysis in Section 2, we model each policyholder's surrender decision as a function of the (1) yield curve, (2) contract return, and (3) contract age.[26]

We consider a policyholder at year-begin t who has started investing in a savings contract at year-end h, $h < t$. The current cash value is $v_{t-1}^h = V_{t-1}^h / N_{t-1}^h$ and the surrender value is $sv_{t-1}^h = SV_{t-1}^h / N_{t-1}^h$, both based on year-end $t-1$ (we use small letters to indicate contract-level variables and large letters to indicate cohort-level variables). Without loss of generality, we assume that policyholders pay accumulated fees (to cover administrative costs) at the earlier of surrender and maturity date. Cumulative fees are a share $1 - e^{-c(t-h-1)}$ of the contract payout, where $c(\cdot)$ is a non-negative function that increases with contract age $t-1-h$.[27] Thus, the surrender value net of (administrative) fees is $sv_{t-1}^h \cdot e^{-c(t-h-1)}$.

Surrendering the contract results in additional transaction costs $\mathcal{G} > 0$ borne by the policyholder. For instance, the policyholder loses the possibility of converting the contract into an annuity at maturity and surrendering may be time-consuming. These costs can be partly offset by the value of satisfying liquidity needs $\mathcal{L} > 0$, e.g., arising from unemployment, medical expenses, or new consumption opportunities. We will assume that $\mathcal{L} - \mathcal{G}$ varies across policyholders, reflecting differences in transaction costs and liquidity needs. The net value of surrender is then $sv_{t-1}^h \cdot e^{-c(t-h-1)} \cdot e^{\mathcal{L}-\mathcal{G}}$.

A policyholder surrenders her contract if the value of surrender exceeds the present value of holding on to the policy,

$$sv_{t-1}^h \cdot e^{-c(t-h-1)} \cdot e^{\mathcal{L}-\mathcal{G}} > \mathcal{M}_{t-1}^h \cdot e^{-c(T^h-h)}, \tag{5}$$

where $\mathcal{M}_{t-1}^h \cdot e^{-c(T^h-h)}$ is the net (of fees) present value of holding the life insurance contract until maturity T^h.[28] We assume that policyholders extrapolate contract returns using the current contract return, implying that $\mathcal{M}_{t-1}^h = v_{t-1}^h \left(\frac{1+\tilde{r}_{P,t-1}^h}{1+r_{f,t-1,T^h-(t-1)}} \right)^{T^h-(t-1)}$, where $r_{f,t-1,T^h-(t-1)}$ is the German government bond rate in year $t-1$ for maturity $T^h-(t-1)$. This assumption is consistent with the observation that life insurers mainly compete over realized contract returns in practice.[29]

to additionally smooth the distribution of asset income over time, which is discussed by Hombert and Lyonnet (2019).

[26] For a discussion about the challenges of modeling policyholder behavior in life insurance, we refer to Bauer et al. (2017).

[27] We use the convention of assigning a contract age of zero at year-begin $t = h+1$ to a contract that was initially invested in at year-end $t-1 = h$.

[28] We emphasize that this model does not necessarily reflect the *optimal* exercise of surrender options by rational and risk-neutral policyholders (as, e.g., in Förstemann, 2019). Instead, our goal is to propose a structural model that can be calibrated with existing empirical data. This approach is also warranted by Hambel et al. (2017)'s result that a calibrated rational-expectations life-cycle model produces much lower surrender rates than empirically observed and by survey evidence from Gottlieb and Smetters (2021) that behavioral biases affect surrender decisions.

[29] Moreover, numerous studies highlight the low level of financial literacy among consumers (e.g., Lusardi and Mitchell, 2014) and that it correlates with surrender decisions (Nolte and Schneider, 2017). This suggests that consumers are likely to evaluate their contracts based on observable characteristics, such as the current contract

The surrender condition in Equation (5) is then equivalent to

$$\mathcal{L} - \mathcal{G} > \log \vartheta^{-1} \left(\frac{1 + \tilde{r}^h_{P,t-1}}{1 + r_{f,t-1,T^h-(t-1)}} \right)^{T^h-(t-1)} - \Delta c_t, \tag{6}$$

where $\mathcal{L} - \mathcal{G}$ is the liquidity need less transaction costs, and the right hand side is the present value of holding the life insurance contract relative to its surrender value less of future fees $\Delta c_t = c(T^h - h) - c(t - h - 1)$.[30] Thus, smaller future contract fees Δc_t reduce the incentive to surrender. Marginal fees for life insurance contracts are typically decreasing with contract age. Decreasing marginal fees imply that $c(\cdot)$ is concave, $c''(\cdot) < 0$.[31] We parametrize $c(x) = k \cdot \log(2 + x)$ with $k > 0$ for contract age $x = t - h - 1 \geq 0$.

If $\mathcal{L} = \mathcal{G}$ and $\Delta c_t \equiv 0$, the model boils down to a comparison between a contract's present value and surrender value. Instead, heterogeneity in (net) transaction costs and contract age enables us to calibrate the model to empirically observed surrender rates. For this purpose, we make the simplifying assumption that $\mathcal{L} - \mathcal{G}$ is normally distributed across policyholders, with expected value μ_L and variance σ_L^2 independently across policyholders and time. Then, the probability that a randomly selected policyholder in cohort h surrenders is given by

$$\lambda^h_t = 1 - \Phi\Bigg(\underbrace{\frac{-k \cdot \log(2 + T^h - h) - \mu_L}{\sigma_L}}_{=\beta_0} + \underbrace{\frac{1}{\sigma_L}}_{=\beta_1} \cdot \log \frac{\mathcal{M}^h_{t-1}}{SV^h_{t-1}} + \underbrace{\frac{k}{\sigma_L}}_{=\beta_2} \cdot \log(2 + (t - h - 1)) \Bigg), \tag{7}$$

which is the surrender rate in cohort h in year t. $\Phi(\cdot)$ is the cumulative distribution function of the standard normal distribution. We estimate β_0, β_1, and β_2 using BaFin's *Erstversichererstatistik* as described in Appendix D.1.

The resulting calibration is illustrated in Figure 3. Surrender rates are monotonically declining with the contract return, which boosts the opportunity cost of surrender. A longer time to maturity (i.e., younger contract age) increases the interest-rate sensitivity of the surrender rates, which results in a steeper line in Figure 3. The level of surrender rates is consistent, e.g., with empirical evidence from Section 2 and from the U.S. (Gottlieb and Smetters, 2021). When the contract return approaches zero, the surrender rate is around 20%, which resembles the stress scenario estimated by Biagini et al. (2017) for German surrender rates.

3.1.3 Balance Sheet and Portfolio Allocation. The insurer's contract portfolio consists of several cohorts, i.e., generations of insurance contracts. Contracts in our model have a total lifetime of $T^h - h = 40$ years (if not surrenders) but differ according to age and their contract begin, which

return.

[30] Note that only *future* fees are relevant for the surrender decision, since fees for preceding contract years are sunk costs.

[31] For example, German life insurers must deduct fees from surrender values evenly distributed across a contract's first 5 years (see German insurance contract law, Section 169), implying decreasing marginal costs. To simplify the computation, we assume a continuous cost function (instead of a step function).

determines the guaranteed return. At the starting point of our model (the end of year $t = 0$, calibrated to 2015), the insurer's contract portfolio features 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. To compute the relative size of cohorts, we draw on the historical evaluation of annual life premiums written, average surrender rates, and contract returns in Germany, and extrapolate where needed, as described in Appendix D.2. The resulting initial contract portfolio exhibits an average guaranteed return of 2.74% per contract (see Table 3), which is consistent with that reported by Assekurata Cologne (2016) reporting an average guaranteed return of 2.97% for German life insurers in 2015. Moreover, the initial portfolio exhibits a modified duration of roughly 14.1 years, which coincides with the median liability duration of German life insurers according to the German Insurance Association (2015).

The insurer invests in four different asset classes: (1) German, French, Dutch, Italian, and Spanish government bonds, (2) AAA, AA, A, and BBB-rated corporate bonds, (3) a European stock market index and (4) a European real estate index. 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 weight (in market values) and duration of each asset class are calibrated based on (German Insurance Association (GDV), 2016) and (EIOPA, 2014, 2016), as detailed in Appendix D.3. The overall duration of investments is consistent with evidence from the German Insurance Association and Assekurata Cologne (2016). Fixed income investment are the most important asset class, with 55% of assets invested in government bonds and 34% in corporate bonds. The allocation of fixed income assets across ratings is skewed toward higher-rated assets, consistent with Assekurata Cologne (2016). All bonds are purchased at par and pay annual coupons. Bonds' time to maturity differs across bonds, such that within each bond category the oldest bond is due in 1 year and the youngest in 20 years for government bonds and 10 years for 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 time $t = 0$, we determine the insurer's leverage to match a ratio of equity capital to total assets (both at market value) of 9%. This assumption is motivated by EIOPA (2016), who report 8.8% equity capital relative to total assets for German life insurers in January 2016.[32] It is also consistent with the ratio of market equity to total assets of listed European life insurers in 2015.[33] The resulting initial calibration, as reported in Table 3, closely matches the balance sheet of German life insurers in 2015. Supporting our

[32] Specifically, EIOPA (2016, Figure 10) reports that total assets divided by total liabilities is 109.5% for a large sample of German insurers (with 75% market share) that consists almost entirely of life insurers. This corresponds to a capital ratio of 8.8%. Since we largely follow EIOPA's approach to compute life insurance liabilities, this capital ratio is adequate for calibrating our model.

[33] 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 then ranges from 2.4% to 13.7% at the 10th and 90th percentile, respectively.

calibration of the insurer's allocation, our model predicts an average investment return of 2.6% for 2016 ($t = 1$), which closely resembles the average investment return of German life insurers in 2016 (3.04% as reported in BaFin's *Erstversichererstatistik*).

We explore two possible investment strategies. First, in the baseline results, we assume that the insurer holds constant the relative portfolio weights at market values. This investment strategy is plausible for insurers to maintain a similar level of investment risk and asset duration over time. Second, in a sensitivity analysis, we implement a duration matching strategy. For this purpose, we assume that the insurer maintains a constant relative duration gap, which is

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

where D_0^A is the initial asset duration and $\tilde{D} < 1$ the target duration gap.Each year, the insurer re-computes the duration of liabilities D_t^L based on the contract portfolio. The insurer then adjusts the asset duration to maintain the duration gap $\tilde{D}$.

3.1.4 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 Appendix D.4. 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 Appendix D.5.

We simulate 10 000 paths of our model with a length of 10 years in Matlab. Figure 4 (a) illustrates that the dynamics of simulated interest rates and stock prices closely resemble those historically observed. In order to assess the risk posed by surrender options in the tail of the distribution, among all simulated paths, we focus on the 5% with the largest average increase in the 10-year German government bond rate (between $t = 0$ and $t = 10$). This gives our exercise the flavor of a stress test. Figure 4 (b) focuses on these paths with an interest rate rise. On average, interest rates annually increase by 25bps in these scenarios. This pace is plausible compared to the historical evolution of German government bond rates, and matches the 75th percentile of annual changes in the 10-year German government bond rate since 1980.[34]

3.1.5 Liquidity, Asset Sales and Price Impact. At the end of each year t, (1) the insurer pays out surrendered contracts, (2) investment returns realize, (3) contract returns are credited to non-surrendered contracts, (4) active (non-surrendered and non-maturing) policyholders pay premiums, and (5) a new contract cohort is created. These elements determine the insurer's free cash flow, which is the difference between cash inflow (premiums, investment income, and bond redemptions) and cash outflow (maturing and surrendered contracts). Given the free cash flow, the

[34] We emphasize that it is beyond the scope of this paper to discuss the plausibility of an interest rate changes from a macroeconomic perspective.

insurer purchases or sells assets in order to match target portfolio weights. Following prior studies (e.g., Greenwood and Vayanos, 2010; Greenwood et al., 2010; Greenwood and Vissing-Jorgensen, 2018; Jansen, 2021; Vayanos and Vila, 2021), we assume that asset markets are segmented into investor clienteles, in particular across bond maturities, which implies that insurers' asset sales have price impact.[35] This is consistent with prior studies on insurers' price impact, e.g., in bond markets (Ellul et al., 2011; Greenwood and Vissing-Jorgensen, 2018; Bretscher et al., 2020; Girardi et al., 2021; Jansen, 2021; Kubitza, 2021; Liu et al., 2021), and investors' price impact more generally (Koijen and Yogo, 2019). Specifically, we assume segmentation into bonds with a remaining time to maturity of (1) up to 10 years, (2) more than 10 years, and (3) stocks and real estate.[36] Then, the market value of total assets at year-end t after realization of cash flows and re-adjustment of the insurer's investment portfolio 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. We denote by w_t^k the weight for asset class $k \in \mathcal{K} = \{\text{short-term bonds, long-term bonds, stocks \& real estate}\}$ at time t and by a_{t-}^k the market value of assets in class k at time $t-$ (i.e., before cash flows realize). Net sales in asset class k are thus equal to $-(w_t^k A_{t+} - a_{t-}^k)$.

The price impact of asset sales is given by δ. We follow Greenwood et al. (2015) and assume that $\delta = 10^{-4}$ (1 bps) per EUR 1 billion sold. This calibration is consistent with the price impact of U.S. insurers' fire sales after corporate bond downgrades (Ellul et al., 2011). We assume that the prices revert within one year, in line with empirical evidence that reversals typically happen within 6 to 8 months (Ellul et al., 2011; Massa and Zhang, 2021; Kubitza, 2021).

When interest rates rise, policyholders with similar insurance contracts face a similar increase in surrender incentives across different insurers. To take such correlated surrender incentives into account when estimating the total volume of asset sales, we scale the insurer's size to the volume of European life insurance contracts with surrender options, Ω. This is a sensible benchmark due to a common economic environment and monetary policy, in particular. Specifically, scale the insurer's insurance reserves to 80% of European life insurance reserves excluding non-participating contracts in 2016Q3, which corresponds to EUR 5.238 trillion. [37]

[35] Insurers' asset sales are especially relevant from a financial stability perspective as they might contribute to systemic risk (EIOPA, 2017b; Liu et al., 2021). Therefore, we focus on the price impact of asset sales. Accounting for the price impact of asset purchases would have a negligible effects on our results since we focus on scenarios in which the insurer's free cash flow is negative and, thus, asset purchases are mostly absent.

[36] Alternative definitions of segments yield similar results.

[37] German life insurance reserves account for roughly 19% of European life insurance reserves (EIOPA, 2020). Whereas our model is calibrated to 2015, the earliest available details on European life insurance reserves at market-consistent accounting (following the Solvency II standards) reported by EIOPA (2020) 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 roughly 2% relative to 2016Q3), we use the value from 2016Q3 to calculate fire sale costs. The scaling factor is conservative for two reasons. First, insurers may also have to sell assets when non-participating contracts are surrendered, which we, nonetheless, exclude because surrender dynamics may

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

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

The price impact reflects externalities generated by asset sales on other institutions.[38] 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 liability duration). δ and Ω are exogenous parameters. Given these variables, we use Equation (10) to find the final market value of total assets A_{t+}.[39] The solution for A_{t-} then determines fire sale costs and the asset allocation.

When calculating asset sales, we make two important assumptions. First, insurers do not fund surrender payments by taking on additional debt instead of selling assets. This assumption is motivated by the observation that surrender payments substantially exceed life insurers' financial liabilities. For example, surrender payments correspond to more than 6 times the volume of their financial liabilities to credit institutions (EIOPA, 2020). Second, policyholders do not immediately invest surrender values in the same assets that insurers sold. Instead, policyholders might consume part of the surrender value to satisfy liquidity needs. Consistently, in Appendix C we estimate that a 1% increase in aggregate German surrender payments associated with a 0.65% increase in aggregate private consumption. Since guaranteed returns react with a substantial time lag to changes in interest rates, specified by regulation, insurers are not able to offer contracts with significantly higher guaranteed rates to surrendering policyholders and insurers' long-term investment prevent them from significantly raising contract returns. These observations suggest that our model delivers a useful benchmark for surrender-driven asset sales.

3.2 Baseline Results

The following results are based on the 5% simulated paths of our model with the largest average increase in the 10-year German government bond rate (between $t = 0$ and $t = 10$).

be different than in our model. Second, we are likely to underestimate the share of contracts that can be surrendered in practice since EIOPA (2019) reports that only 12% of European life insurance reserves for participating contracts have no surrender option.

[38]For example, in Allen and Carletti (2006)'s model, forced asset liquidation by insurers translate into low asset prices that impair the hedging activities of banks holding the same asset.

[39]We solve Equation (10) numerically and choose the solution with minimal fire sale costs if several numerical solutions exist.

3.2.1 Slow Pass-Through of Interest Rates.

Figure 5 (a) depicts the dynamics of interest rates, the insurer's investment return and contract returns. The simulated 10-year German government bond rate gradually increases by roughly 25bps per year. However, the insurer's investment return decreases. The reason 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 increasing yet relatively lower yields. Given the initial asset duration of 9.4 years, it takes roughly the same time until the average bond rate in the insurer's investment portfolio increases. Thus, there is a slow pass-through of changes in interest rates to the insurer's investment return.

Figure 5 (a) illustrates that contract returns closely follow the insurer's investment return. This is intuitive since, during an interest rate rise, existing contracts have relatively low guaranteed returns (implied by previously low interest rates) and, thus, are not binding. Therefore, the slow pass-through of an interest rate rise to the insurer's investment return translates into a slow pass-through to contract returns.

Guaranteed returns for new contracts also do not increase but tend to decline. The reason is that guaranteed returns are based on a moving average of lagged interest rates and, therefore, are mostly driven by historically declining interest rates, similarly to the declining investment return.

Due to these return dynamics, the gap between contract return and interest rate, i.e., the *excess* contract return, shrinks. As a result, incentives to surrender strengthen. The model predicts that surrender rates increase from an average rate of roughly 3% at model begin to almost 20% after 10 years of rising interest rates, as Figure 5 (b) illustrates. This level of surrender rates is large but still plausible. For example, it corresponds to the surrender stress scenario estimated by Biagini et al. (2017).[40]

3.2.2 Interest Rate Convexity.

The increase in surrender rates directly reduces the (interest-rate) duration of existing insurance contracts. Moreover, the relative weight of cohorts in the insurer's contract portfolio changes. Large maturing cohorts, which benefited from large contract returns at a young contract age (especially in the years before 2005), are substituted by relatively smaller cohorts over time since these faced relatively smaller contract returns. Thereby, young cohorts with a longer time to maturity, and, thus, longer duration, gain more weight relative to older cohorts. These dynamics in the relative size of cohorts amplify the effect of rising interest rates on the *average* duration of the insurer's contract portfolio.

To disentangle the two effects, we compare our results to a counterfactual calibration in which surrender rates are constant across policyholders and time. In this counterfactual calibration, policyholders only surrender due to idiosyncratic liquidity needs. In this case, the duration of life insurance contracts is decreasing, consistent with the dynamics described above (see Figure 6 a). The average modified duration of the contract portfolio declines from 14 years at $t = 0$ to roughly

[40] It is important to note that the correlation between surrender rates and interest rates is stronger in our simulations than in the empirical analysis in Section 2 since we focus on the tail event of a relatively large *and* persistent interest rate rise.

11 years at $t = 10$.

The decline in contracts' duration is substantially larger when surrender rates are interest-rate sensitive, as in our baseline calibration. In this case, the modified duration shrinks from 14 years at $t = 0$ to roughly 6 years at $t = 10$. The difference to the case with a constant surrender rate is due to the effect of re-allocation of cash flows over time *within* contracts: policyholders are more likely to surrender earlier than later. As a result, contracts' duration declines by additional 4 to 5 years and even below the duration of the insurer's assets. Therefore, surrender options lead to life insurance convexity. Importantly, due to convexity, a gradual but long-lasting interest rate rise can reverse life insurers' duration gap. Starting with a negative duration gap, i.e., longer contract than asset duration, the duration gap becomes positive after 4 years. Then, insurers' equity switches from a long to a short position in interest rates.

3.2.3 Free Cash Flow and Asset Sales. Large surrender rates translate into large surrender payments to policyholders. These negatively affect the insurer's free cash flow, as Figure 6 (b) illustrates. In the counterfactual calibration with constant surrender rates, the free cash flow stays positive at roughly 2% of the previous year's total assets. In this case, the inflow from asset investments and new insurance premiums is more than sufficient to pay for maturing and surrendering policyholders. In contrast, in the baseline calibration, increasing surrender rates depress the free cash flow into negative territory from year $t = 4$ onward. The longer the interest rate rise lasts, the more negative becomes the free cash flow, with up to 3% of total assets after 10 years of rising interest rates.

As a result, the insurer is forced to sell assets. We estimate forced asset sales of up to 4% of assets after 10 years of rising interest rates, as Figure 7 illustrates. These asset sales plausibly depress asset prices by up to 90bps. This price impact is economically significant. For example, Massa and Zhang (2021) document that nonfinancial firms react to corporate bond price declines of roughly 50bps resulting from fire sales of hurricane-Katrina exposed insurance companies. Thus, the economic magnitude of surrender-driven price impact is significant. Importantly, the volume of asset sales and, thus, the price impact increases wit the length of an interest rate rise. The reason is that an enduring interest rate rise prevents the insurer's investment return from catching up with interest rates (see Figure 5).

Whereas the price impact is potentially large, in additional results we find that the resulting total costs are small relative to the life insurer's equity capital, namely roughly 10bps (see Appendix E). Thus, the effect of surrender-driven asset sales on financial markets dominates that on life insurers' balance sheet.

3.3 Sensitivity: Role of Long-Term Investments

We argue above that the mechanism through which an interest rate rise triggers asset sales is the slow pass-through of interest rate changes to contract returns. Intuitively, long duration of the insurer's assets reduces their market value when interest rate rise, dis-incentivizing policyholders to keep on investing in the insurer. We explore this channel by using counterfactual calibrations of our model. For this purpose, we vary the duration of fixed income assets (proportionally across asset classes) and re-simulate the model. Again, we focus on the 5% simulated paths with the largest average increase in the 10-year German government bond rate.

Figure 8 shows that a higher asset duration reduces the insurer's investment return. The investment return in an average year declines by roughly 1 percentage point when the asset duration increases from 7.5 to 12.4 years.[41] As a result, surrender incentives increase and cause a rise in the average surrender rate by more than 2 percentage points.

This increase in surrender activity forces the insurer to sell more assets. The model implies that asset sales in an average year more than triple when the asset duration increases by roughly 5 years. Therefore, a long asset duration significantly amplifies surrender-driven asset sales.

3.4 Sensitivity: Role of Investment Strategies

In the baseline results, we assume that the insurer keeps the relative weights across assets constant over time. However, when the contract duration declines as a result of rising interest rates (see Figure 6), insurers are likely to reduce their asset duration, as well. We implement such a dynamic investment strategy in a counterfactual calibration, assuming the insurer targets a constant relative duration gap between assets and contracts. Again, we focus on the 5% simulated paths with the largest average increase in the 10-year German government bond rate.

Figure 9 depicts the resulting asset sales and price impact under the dynamic investment strategy. We find that the peak asset sales and price impact are comparable to those when the insurer targets constant portfolio weights. However, there is a substantial difference in their timing. Whereas asset sales and price impact become larger over time with constant portfolio weights, with a dynamic investment strategy the largest effects realize in the first years of an interest rate rise. After roughly 5 years, our model predicts that asset sales and price impact revert and stabilize at low levels.

The reason is that the insurer prevents 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 increases the pass-through of interest rate changes later on, which reduces surrender rates (we document the evolution of the free cash flow and surrender rates in Appendix E). Figure 10 provides corresponding evidence. Here, we compare the asset sales by asset class under a dynamic investment strategy with those under constant portfolio weights. In addition to the difference in timing, we find a substantial difference in terms of the assets being sold. When the insurer follows a dynamic investment strategy, it sells almost exclusively long-term bonds in order to reduce the asset duration, matching the declining duration of insurance contracts. Instead, when the insurer targets constant portfolio weights, it sells almost exclusively short-term bonds. The reason is that longer-term bonds are

[41] In EIOPA (2016)'s stress test, participating insurers' (mostly life insurers') asset duration ranged from 2.73 (Cyprus) to 12.45 (U.K.) years at the country-average, as of January 2016. Thus, the asset duration in counterfactual calibrations is in the upper half of the distribution.

generally more interest-rate sensitive and, thus, their market value declines relative to that of shorter-term bonds when interest rates increase. To counteract this shift in relative market values, the insurer sells long-term rather than short-term bonds.

4 Empirical Predictions and Policy Implications

Our analysis sheds light on the interaction between interest rates, surrender options, and life insurers' asset sales. Thereby, we derive several empirical predictions.

First, we uncover substantial convexity in the interest rate sensitivity of life insurance savings contracts. In our baseline calibration, the duration of life insurance contracts drops by roughly 4 to 5 years during an interest rate rise due to the provision of surrender options with guaranteed surrender values. This convexity lowers the interest rate sensitivity of life insurers' liabilities when interest rates increase. This prediction is consistent with empirical evidence on the interest rate sensitivity of life insurers' equity prices. For example, by comparing U.S. life insurers (that typically supply surrender options with guarantees) to U.K. life insurers (that do typically *not* guarantee surrender values), Hartley et al. (2017) document that U.S. life insurers' equity prices become relatively less interest-rate-sensitive when interest rates increase. Convexity implies that it can be optimal for life insurers to maintain a negative duration gap (i.e., a longer asset than contract duration) in order to reduce their exposure to an interest rate rise. This result provides a possible explanation for why life insurers in most countries exhibit negative duration gaps (e.g., IMF, 2019).[42]

Second, convexity incentivizes insurers to reduce (increase) the duration of their assets upon an interest rate rise (decline) to match changes in contract duration. A collective re-balancing can induce price pressure on long-term relative to short-term interest rates, analogously 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 empirically document that German life insurers increase asset duration upon an interest rate decline and that the increased demand for long-term bonds further reduces long-term yields. Ozdagli and Wang (2019) provide additional empirical evidence for a negative correlation between demand for long-term bonds by U.S. life insurers and the level of interest rates.

Third, our results suggest that surrender options can force life insurers to liquidate a substantial share of their assets. Under plausible assumptions, we estimate an asset price impact of such asset liquidations of up to 90bps. A longer asset duration can substantially amplify the effect. Thus, our model predicts a positive correlation between surrender rates and life insurers' asset sales, and a negative correlation between surrender rates and the prices of insurers' initial investments. The latter effect further amplifies the price impact from re-balancing across maturities (see above) during an interest rate rise (with increasing surrender rates), but (partly) offsets re-balancing-induced price impact during an interest rate *decline* (with decreasing surrender rates). Asset sales

[42] It is important to note that negative duration gaps also 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.

and their price impact may be amplified by other liquidity shortages of life insurers during an interest rate rise, such as the obligation to post variation margins for interest rate swaps (De Jong et al., 2020).[43]

Asset sales arise because surrender values do not react to (short-term) asset price fluctuations and, therefore, insurers *collectively* face an increase in surrender rates. Instead, decoupling surrender incentives from asset prices can reduce common exposure across insurers and, thereby, correlated asset sales. One possibility to decouple surrender incentives and asset prices is to allow surrender values to fluctuate with asset prices. If, for example, in our model surrender values were equal to the present value of future contract returns, surrender incentives would be independent of interest rates (cf. Equation 6). Market value adjustments (MVAs), which are common during the first years of U.S. life insurance contracts, take one step in that direction by adjusting surrender values to changes in interest rates (see, e.g., Förstemann, 2019). However, MVAs are not common practice in many European life insurance markets. This observation suggests that it is individually optimal for life insurers not to offer them, e.g., because the liquidity provided by life insurance contracts is highly valued by policyholders. However, to mitigate life insurers' price impact when interest rates rise, MVAs can be a viable policy tool.

In contrast to MVAs, large surrender penalties might also reduce surrender rates but are costly for policyholders even in times with declining interest rates and negligible fire sale externalities. Similarly, the temporary suspension of surrender payments can mitigate the (short-term) impact of collective surrenders, however at the expense of policyholders with high liquidity need.[44] Thus, although policymakers consider surrender suspensions as a valid policy instrument and suggest to use surrender penalties for the purpose of managing life insurers' liquidity risk (e.g., ESRB, 2020), our findings suggest that the use of MVAs can be more efficient to mitigate surrender-driven fire sale externalities.

5 Conclusion

Surrender options allow life insurance policyholders to terminate their contracts before maturity and receive an ex-ante guaranteed surrender value. Because this option moves toward the money when interest rates increase, yield-maximizing policyholders then have stronger incentives to surrender. This implies that life insurance contracts display convexity: their duration decreases with the level of interest rates.

In a large panel dataset, we empirically document this phenomenon. Using the U.S. federal funds rate as an instrument, we provide empirical evidence of a causal effect of interest rates on surrender rates. Exploiting heterogeneity across insurance companies, we argue that this effect is

[43] De Jong et al. (2020) estimate that variation margin payments due in the event of a parallel 25bps upward shift in interest rates would exceed the cash of 24% of European insurers in their sample.

[44] The French *Sapin 2* law allows regulators to temporarily (for up to 3 months) limit the payment of surrender values. The legislation is specifically designed to strengthen financial stability in case collective surrenders during a sudden rise in interest rates lead to fragility among life insurers (`https://m.ca-assurances.com/en/magazine/sapin-2-law-what-it-will-change-insurance-sector`).

due to policyholders maximizing yield.

A sufficiently strong increase in surrender rates can force life insurers to sell assets, generating price impact due to insurers' importance as asset investors. We present and calibrated a granular model to estimate surrender-driven asset sales and price impact. Simulations predict that an interest rate rise of 25bps per year boosts surrender rates from below 5% to roughly 20% after 10 years. These large surrender rates are estimated to force insurers to sell up to 3% of their assets, depressing asset prices by up to 90bps. Asset sales increase with the duration of insurers' assets, which prevents policyholders to benefit from rising interest rates and, thereby, amplifies surrender rates. When insurers follow a dynamic investment strategy, targeting a constant duration gap, asset sales and price impact affect predominantly long-term assets and realize early after interest rates have started to rise and revert after roughly 5 years. Instead, when insurers target constant portfolio weights, asset sales and price impact increase over time and affect predominantly short-term assets. These results highlight the importance of insurers' investment behavior for the level, timing, and allocation of fire sale externalities caused by surrender options.

We discuss several empirical predictions of our model and policy measures to mitigate fire sale externalities. A potential remedy is to align surrender values with asset prices, which would lower the sensitivity of surrender incentives to interest rate changes.

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Figures and Tables

Figure 1. Economic significance of surrender payments in Europe.

The figure depicts the ratio of total life insurance surrender payments in European countries to (a) total payouts to life insurance policyholders and (b) life insurance premiums net of reinsurance ceded. The distribution is weighted by total life insurance reserves. The data include Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Liechtenstein, Lithuania, Luxembourg, Malta, Netherlands, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, and the U.K. *Source: EIOPA (2020).*

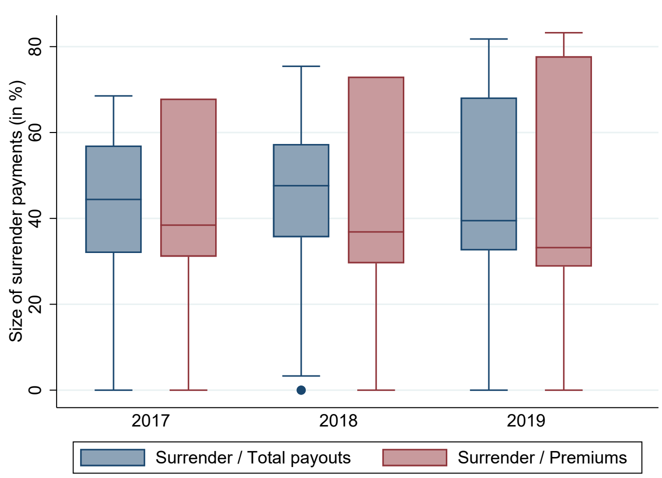
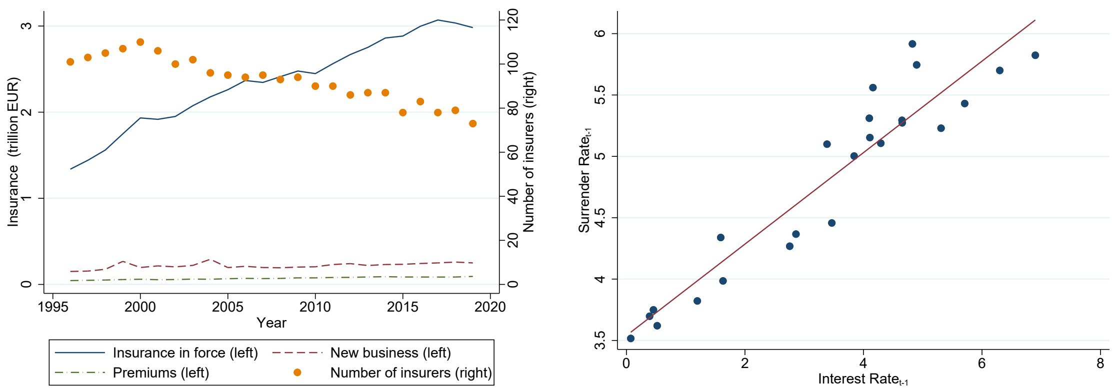


Figure 2. Sample Characteristics and Visual Inspection of Surrender and Interest Rates.
Figure (a) depicts the total volume of existing insurance in force at the end of each year, total insurance premiums, and the total volume of new business in trillion EUR (left axis), and the number of insurers in each year (right axis) in the sample. Note that new business is measured by volume insured and, thus, on average exceeds premiums. 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.

Figure 3. Surrender rate calibration.
The figure depicts the surrender rate for 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 surrender penalty $\vartheta = 1 - \vartheta = 2.5\%$.

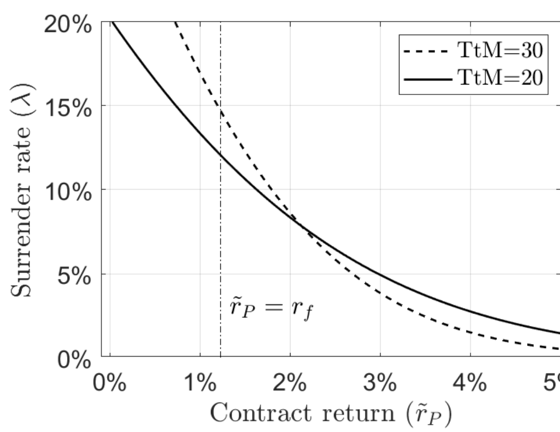
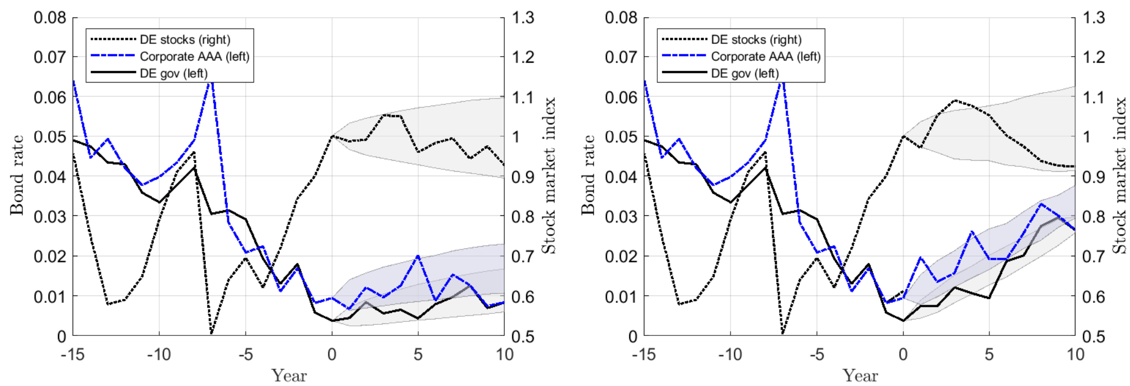
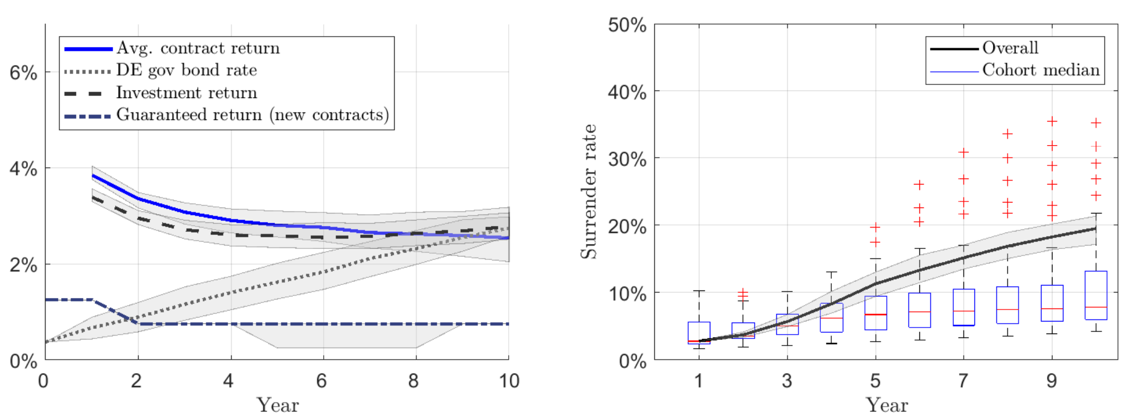


Figure 4. Financial Market Dynamics: Historical and Simulated.
The figures depicts a sample path and the 25th / 75th percentiles of simulated 10-year German government bond rates, AAA corporate bond rates, and the European stock market index from year 0 on. Prior to year 0, we show the actual historical evolution, up to year 0, which corresponds to 2015. Figure (a) displays all simulated paths and (b) only those with the 5% largest average increase in the 10-year German government bond rate.



(1) All Paths. (2) Paths with Rising Interest Rates.

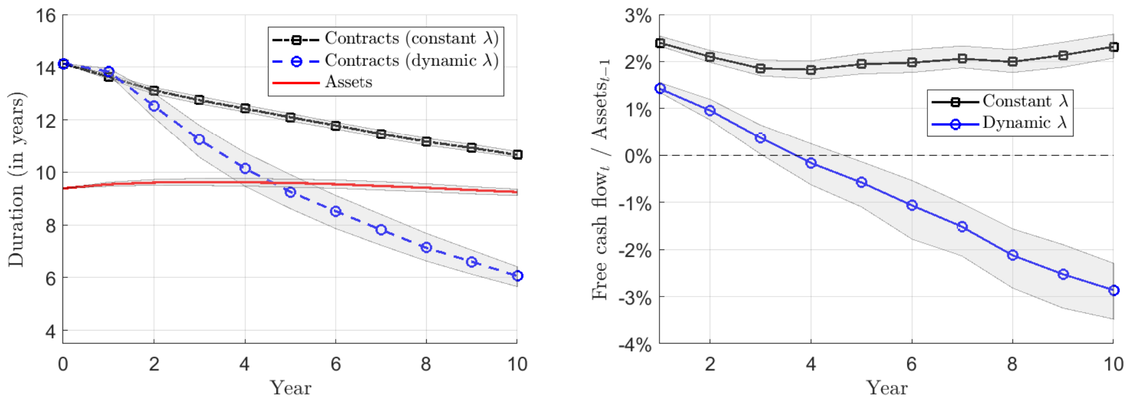
Figure 5. Interest Rate, Contract Return, and Surrender Rate.
Figure (a) depicts the simulated contract return for an average cohort, 10-year German government bond rate, the insurer's investment return, and the guaranteed return for new contracts (median and 25th / 75th percentiles). Figure (b) depicts the share of surrendered contracts (median and 25th / 75th percentiles; straight lines) 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.

Figure 6. 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 surrender rate (squares), and of the insurer's contract portfolio if surrender rates respond to the market environment (circles). The asset duration does not differ with the specification of surrender dynamics. Figure (b) depicts the insurer's free cash flow relative to the previous year's total assets for the same two surrender dynamics. We show the median and 25th / 75th percentiles in each year.



(a) Duration.

(b) Free Cash Flow.

Figure 7. Asset Sales and Price Impact.

The figure depicts the insurer's asset sales relative to previous year's total assets (left axis) and the average price impact (right axis). The average price impact is calculated as the price impact per EUR sold, defined as the average asset class-specific price impact, as defined in Equation (9), weighted by asset class-specific volume of sales. The figure shows the median and 25th/75th percentile for each year.

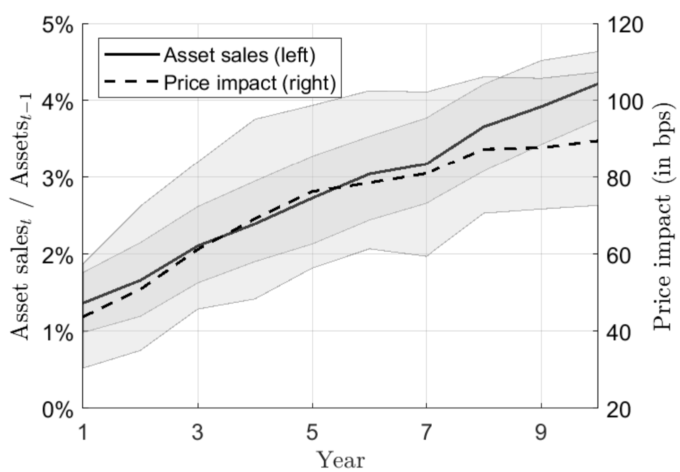


Figure 8. Counterfactual Calibration: Effect of Asset Duration on the Investment Return, Surrender Rate, and Asset Sales.

The figure depicts the insurer's average investment return across time (left axis), the average ratio of asset sales to lagged total assets across time (left axis), and the average surrender rate across time (right axis) at the median and the 25th/75th percentiles. We vary the initial asset duration on the x-axis, holding the relative differences in duration across asset classes constant as in the baseline calibration.

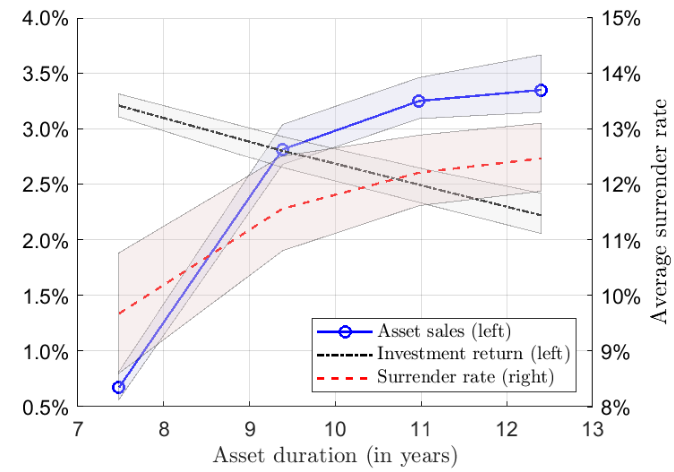


Figure 9. Counterfactual Calibration: Asset Sales and Price Impact with Dynamic Investment Strategy.

The figure depicts the insurer's asset sales relative to 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 sold, defined as the average asset class-specific price impact, as defined in Equation (9), weighted by asset class-specific volume of sales. The figure shows the median and 25th/75th percentile for each year.

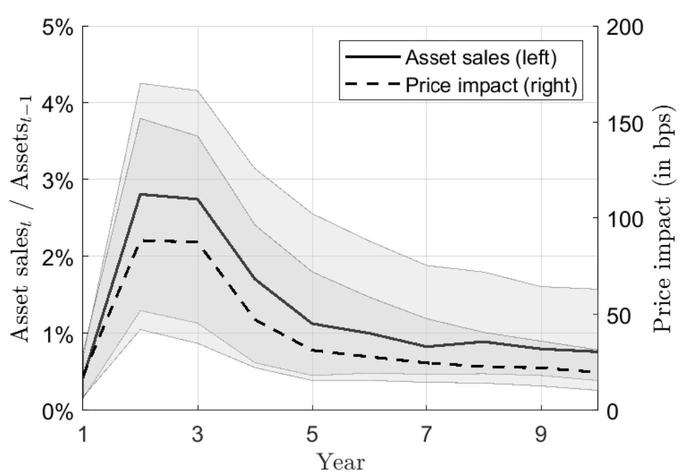
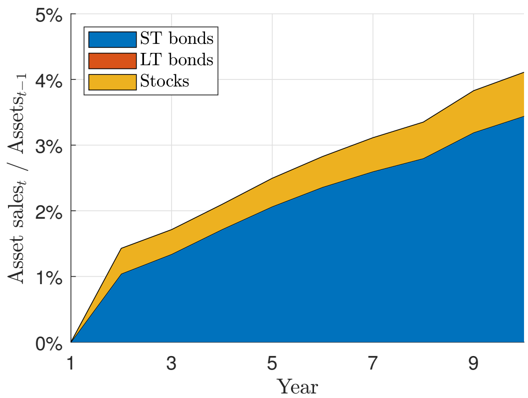
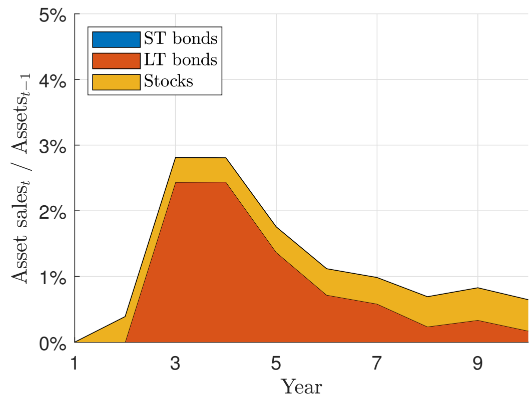


Figure 10. Asset Sales across Asset Classes: The Role of Investment Strategies.

The figures depict the median ratio of asset sales to previous year's total assets for each year and asset class, where short-term (ST) bonds are those with a maturity up to 10 years and long-term (LT) bonds are those with a maturity larger than 10 years Figure (a) assumes that the insurer's investment strategy keeps the asset portfolio weights constant. Figure (b) assumes that the insurer follows a dynamic investment strategy that keeps the relative duration gap constant.



(a) Constant Portfolio Weights.



(b) Dynamic Investment Strategy.

Table 1. Summary Statistics.

Surrender rate, age, new business, and investment return are at insurer-year level retrieved from BaFin's *Erstversichererstatistik*. Remaining variables are at year level, retrieved from German Bundesbank (interest rate), BIS (inflation), OECD (GDP and investment growth), Laeven and Valencia (2018) (crisis indicator), and the German Insurance Association GDV (excess guaranteed return, new endowment, unit-linked, and aggregate business). The sample starts in 1996 and ends in 2019, and includes 159 German life insurers in total.

	N	Mean	SD	p5	p50	p95
Insurer characteristics (insurer-year level)						
Surrender rate$_t$ (in ppt)	2,232	4.88	2.58	1.70	4.50	9.55
New business$_{t-1}$ (in ppt)	2,232	11.88	9.61	2.21	9.56	30.58
Investment return$_{t-1}$ (in ppt)	2,232	4.97	1.66	2.40	4.70	7.60
Macroeconomic characteristics (year level)						
Interest rate$_{t-1}$ (in ppt)	24	3.42	1.96	0.39	3.97	6.30
Guaranteed return$_{t-1}$ (in ppt)	24	2.60	1.03	0.90	2.50	4.00
Fed funds rate$_{t-1}$ (in ppt)	24	2.57	2.38	0.08	1.79	5.96
New term life$_{t-1}$ (in ppt)	24	21.55	6.09	11.43	20.50	29.60
log New business$_{t-1}$	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

Table 2. Surrender Rates and Interest Rates.
The table presents estimates from a specification of the form:

$$\text{Surrender rate}_{i,t} = \alpha \cdot \text{Interest rate}_{t-1} + \beta \cdot X_{i,t-1} + \gamma \cdot Y_{t-1} + u_i + \varepsilon_{i,t}$$

at the insurer-year level from 1996 to 2019. Interest rate$_{t-1}$ is the 10-year German government bond rate. $X_{i,t-1}$ is a vector of insurer-level controls, which includes the 1-year lagged investment return and share of new insurance business. Y_{t-1} is a vector of macroeconomic controls, which includes the 1-year lagged German inflation, GDP growth, investment growth, and a banking crisis indicator as well as the log of total new life insurance contracts and the share of new term life contracts. Guaranteed return$_{t-1}$ is the lagged guaranteed minimum return for new life insurance contracts. New business$_{t-1}$ is the lagged share of new insurance business relative to an insurer's total insurance in force. Columns (1) to (3) report OLS estimates. Columns (4) to (6) report IV estimates with the lagged U.S. federal funds rate, FFR$_{t-1}$, as an instrument for the 10-year German government bond rate. Columns (2) and (5) only include insurer-year observations with at least 9.56% lagged share of new business, corresponding to the median share of new business. Sources: BaFin (insurer-level surrender rate, new business, and investment return), German Bundesbank (interest rate), WRDS (federal funds rate), BIS (inflation), OECD (GDP, investment growth), GDV (level and composition of total new life insurance policies), Laeven and Valencia (2018) (banking crisis indicator). 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					
	OLS			IV		
Sample:	Full	Strong new business	Full		Strong new business	Full
Interest rate$_{t-1}$	0.175***	1.028***		0.173**	1.568***	
	[3.36]	[3.14]		[2.58]	[2.95]	
Interest rate$_{t-1}$ × Guaranteed return$_{t-1}$		-0.333***			-0.580***	
		[-3.22]			[-3.63]	
Interest rate$_{t-1}$ × Guaranteed return$_{t-1}$ ×New business$_{t-1}$			-0.018***			-0.022**
			[-3.69]			[-2.38]
Macro controls	Y	Y	Y	Y	Y	Y
Insurer controls	Y	Y	Y	Y	Y	Y
Guaranteed return$_{t-1}$		Y			Y	
Interest rate$_{t-1}$ × New business$_{t-1}$			Y			Y
Guaranteed return$_{t-1}$ × New business$_{t-1}$			Y			Y
Insurer FE	Y	Y	Y	Y	Y	Y
Year FE			Y			Y
First stage						
FFR$_{t-1}$				0.32***	0.28***	
				[33.86]	[11.33]	
FFR$_{t-1}$ × Guaranteed return$_{t-1}$ ×New business$_{t-1}$						0.34***
						[3.41]
F Statistic				955.1	47.7	178.6
No. of obs.	2,232	1,110	2,232	2,232	1,110	2,232
No. of insurers	159	135	159	159	135	159
Standardized coefficients						
Interest rate$_{t-1}$	0.13	0.63		0.13	0.96	

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

Variable	**Initial value**
Average surrender rate	2.81%
Average guaranteed return	2.74%
Avg. remaining contract lifetime	28.44
Equity capital / assets (MtM)	9.00%
Modified Duration (Contracts)	14.14
Modified Duration (Assets)	9.39

Internet Appendix

A Surrender Options in the U.S.

In the U.S., surrender values differ strongly across life insurance contract types. For individual deferred annuities, the surrender value should at least correspond to 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 begin.[45] Therefore, surrendering policyholders receive a minimum guaranteed value which is independent of market developments.

For modified guaranteed annuities (and variable annuities) a cash surrender benefit also exists. However, the surrender value (at least in the first contract years) depends on a market value adjustment (MVA). This can cause both upward and downward changes based on market developments (NAIC, 2011). In general, the MVA compares interest rates at contract begin 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).[46]

Surrender penalties for U.S. life insurance contracts are typically up to 10% of the contract's cash value in the first year and then decrease by 100bps annually. However, 10% of the cash value can typically be withdrawn without a penalty in the first contract years.

[45]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 125bps (NAIC, 2017).

[46]Usually, the reference interest rate for the MVA is the U.S. Constant Maturity Treasury yield.

B Empirical Analysis: Additional Results

Table IA.4. Surrender Rates and Interest Rates: Robustness.
The table presents estimates from a specification of the form:

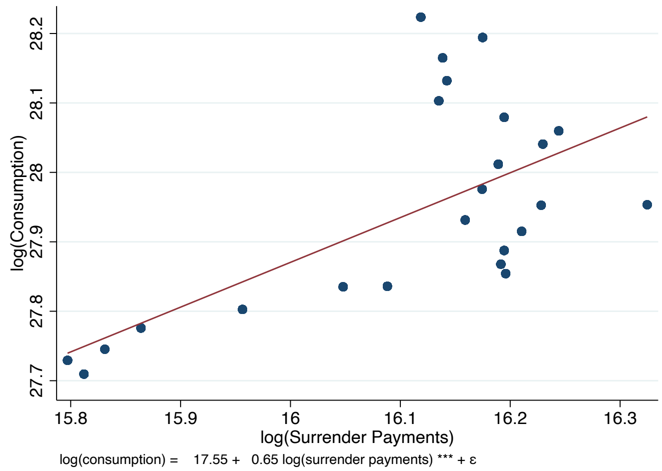
$$\text{Surrender rate}_{i,t} = \alpha \cdot Z_{t-1} + \beta \cdot X_{i,t-1} + \gamma \cdot Y_{t-1} + u_i + \varepsilon_{i,t}$$

at the insurer-year level from 1996 to 2019. Column (1) presents an IV estimate for the effect of the 10-year German government bond rate, $Z_{t-1} = \text{Interest rate}_{t-1}$, instrumented by the lagged U.S. 10-treasury rate. Columns (2) and (3) present a reduced-form estimate for the effect of the federal funds rate, $Z_{t-1} = \text{FFR}_{t-1}$. Column (4) explores potential differences between times of rising and declining interest rates, where $1\{\Delta\text{Interest Rate}_{t-1} < 0\}$ is an indicator for a decline in the interest rate from $t-2$ to $t-1$. $X_{i,t-1}$ is a vector of insurer-level controls, which includes the 1-year lagged investment return and share of new insurance business. Y_{t-1} is a vector of macroeconomic controls, which includes the 1-year lagged German inflation, GDP growth, investment growth, and a banking crisis indicator as well as the log of total new life insurance contracts and the share of new term life contracts. Sources: BaFin (insurer-level surrender rate, new business, and investment return), German Bundesbank (interest rate), WRDS (federal funds rate), BIS (inflation), OECD (GDP, investment growth), GDV (level and composition of total new life insurance policies), Laeven and Valencia (2018) (banking crisis indicator). 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)
Dependent variable:	Surrender rate			
	IV	OLS		
Interest rate$_{t-1}$	0.162***		0.176***	0.203***
	[3.26]		[2.83]	[3.54]
Federal funds rate$_{t-1}$		0.054**	-0.001	
		[2.54]	[-0.04]	
$1\{\Delta\text{Interest Rate}_{t-1} < 0\}$				0.059
				[0.71]
$1\{\Delta\text{Interest Rate}_{t-1} < 0\} \times \text{Interest rate}_{t-1}$				0.030
				[1.35]
Macro controls	Y	Y	Y	Y
Insurer controls	Y	Y	Y	Y
Insurer FE	Y	Y	Y	Y
First stage				
U.S. treasury rate$_{t-1}$	1.026***			
	[89]			
F Statistic	6,437.2			
No. of obs.	2,232	2,232	2,232	2,232
No. of insurers	159	159	159	159

C Correlation Between Surrender Payments and Consumption

Figure IA.11. Correlation between surrender payments and private consumption in Germany. The figure plots the logarithm of annual aggregate surrender payments (x-axis) and the logarithm of total private consumption expenditures (y-axis) in Germany from 1995 to 2019 as scatter points. A univariate regression implies that consumption expenditures increase by 0.65% when surrender payments rise by 1%. *Sources: BaFin (surrender payments), OECD (private consumption expenditures).*

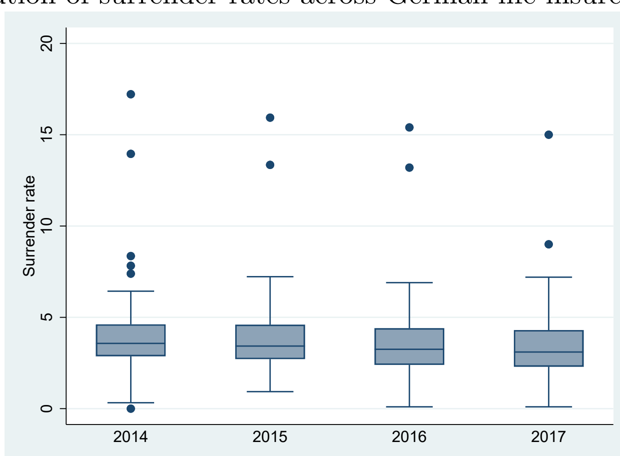


D Model and calibration details

D.1 Calibration of surrender decisions

We calibrate the model of surrender decisions described in Section 3.1.2 exploiting the data on German life insurers' surrender rates described in Section 2. The model inception, $t = 0$, 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 toward the key variables. Due to limited data availability, we use the distribution of surrender rates in 2015. In Figure IA.12, we show that the distribution of the insurer-level surrender rate is similar in 2015 and 2016, as German interest rates were very stable in these years.

Figure IA.12. Distribution of surrender rates across German life insurers.



We then calibrate the model's parameters β_0, β_1, and β_2 as follows, trying to make as few additional assumptions about the distribution of surrender rates as possible:

(1) The insurer's overall surrender rate weighted by insurance in force in the first year of the model, matches the surrender rate of the median German life insurer in 2015 (weighted by contract portfolio size), which is 3.4%.

(2) To calibrate the sensitivity toward contract age, we assume that the surrender rate of contracts in their first year given the average German life contract return and 10-year German government bond rate in 2015 (which were 3.3% and 1.225%, respectively) equals the *early* surrender rate of the median German life insurer in 2015 (weighted by contract portfolio size), which is 6.3%,

$$\lambda_{h+1}^{h} = 1 - \Phi\left(\beta_0 + \beta_1 \log\left(\vartheta^{-1}\left(\frac{1+0.033}{1+0.01225}\right)^{40}\right) + \beta_2 \log(2)\right) \stackrel{!}{=} 0.063. \quad \text{(IA.11)}$$

(3) To calibrate the sensitivity toward contract returns, we match the surrender rate of

contracts in their first year whose contract return matches the discount factor with the *early* surrender rate of the median German life insurer in 2015 (weighted by contract portfolio size) among those insurers with the 10% smallest difference between investment return and 20-year government bond rate, which is 24.6%,

$$\lambda^h_{h+1} = 1 - \Phi\left(\beta_0 + \beta_1 \log\left(\vartheta^{-1}\right) + \beta_2 \log(2)\right) \overset{!}{=} 0.246. \tag{IA.12}$$

Here, the assumption is that an insurer's investment return proxies for its contracts' returns and the 20-year government bond rate a good proxy for the average time to maturity of existing contracts.[47]

The resulting calibration is $(\beta_0, \beta_1, \beta_2) = (0.512, 1.3847, 0.2021)$.

D.2 Calibration of the Initial Contract Portfolio

To calibrate the cash value of contract cohorts at model inception we use:

- the number of new life insurance contracts and the life insurance sector's surrender rate
  - 1996 - 2015: reported by BaFin
  - 1976 - 1995: reported by the German Insurance Association, scaled to the reports from BaFin with the scaling factor implied by filings from 1996
- the realized average contract return of German life insurance policies
  - 2004 - 2015: reported by Assekurata Cologne (2012, 2014, 2016)
  - 1976 - 2003: extrapolated by fitting a linear model to the average contract return reported by Assekurata for 2004-2020 using the prevailing guaranteed return ("Höchstrechnungszins") and the 20-year German government bond rate as independent variables

Denote by N^h the number of new contracts in year $t = h$ and by $\tilde{\lambda}_t$ the average surrender rate (reported by BaFin) in year t in Germany (where $t = 0$ corresponds to 2015). Due to the absence of more granular data, we make the following assumptions: (1) within each cohort h each contract pays a 1 EUR premium each year if not surrendered or matured, (2) each contract has a 40-year duration at inception, (3) each existing contract's surrender rate in year t can be approximated by the average surrender rate $\tilde{\lambda}_t$. However, starting to accumulate contracts in 1976, these assumptions must not necessarily arrive at the representative contract portfolio in 2015. Instead, contracts in practice may deviate from these assumption due to the presence of one-time premiums, heterogeneous surrender rates, and changes in insurance supply (e.g., due to insurer failures).

[47]Note that the investment return is a good 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 3.3% (according to Assekurata Cologne, 2016), while the guaranteed return for new contracts was 1.25%.

To evaluate the representativeness of the implied 2015-contract portfolio, we use two key portfolio characteristics: the average guaranteed return per contract and the modified duration.[48] Assekurata Cologne, 2016 reports an average guaranteed return of 2.97% for German life insurers in 2015 and the German Insurance Association (2015) reports a modified duration of roughly 14.1 years for the median German life insurer. Following the assumption above, our initial portfolio would exhibit a much lower modified duration (10.7 years). Thus, early contracts have a too large weight in the portfolio. To offset this bias, we modify cohort sizes by a multiplicative trend, using

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

as the number of new contracts in year h to accumulate policies.

The larger g, the larger are later-sold contracts relative to earlier-sold policies. This increases the modified duration (but may be offset by heterogeneous contract returns). Eventually, we find that $g = 0.7$ lifts the modified duration up to 14.09 years, matching the reported duration. Finally, we scale $\hat{N}^h$ such that $N^0 = N = 10,000$, which is the number of new contracts for each year $t \geq 0$ in our model.

D.3 Calibration of the Insurer's Investment Portfolio

We calibrate the insurer's asset portfolio weights based on German Insurance Association (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 EIOPA (2014) for German insurers. We allocate the remaining fraction of fixed income instruments to government bonds (55.3%).

The weights within sub-portfolios are based on Berdin et al. (2017) and EIOPA (2014) and reported in Table IA.5. We include a large home bias toward German government bonds,

[48] Consistent with EIOPA, 2016, we calculate a contract's modified duration as

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

where

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

is the present value of contract cash flows at year-end t and $\hat{r}_{P,t+h}$ is the projected contract return for year $t+h$.

which, however, has small impact on our results. Due to the absence of more granular data, we calibrate real estate and stock weights in order to yield a plausible home bias of 60% for German real estate and stocks, and distribute the remaining weights equally.

Table IA.5. 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 German Insurance Association (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%	-
Sovereign 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 of 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 by EIOPA (2016, Table 12) for 2015, implying the scaling factor $\hat{w}_{2015} = \frac{9.3}{(6.9w_{\text{corp}}+9.5w_{\text{sov}})/(w_{\text{corp}}+w_{\text{sov}})} \approx 1.09$. To calibrate heterogeneity within the government bond portfolio, we use the distribution of modified duration of government bonds across countries reported by EIOPA (2016, Table 13) and scale these up to match the average government bond portfolio duration of $9.5 \times \hat{w}_{2015} = 10.4$. Similarly, to calibrate heterogeneity within the corporate bond portfolio, we use the distribution of modified durations of corporate bonds across ratings reported by EIOPA (2016, Table 14) and scale these up to match the average corporate bond portfolio duration of $6.9 \times \hat{w}_{2015} = 7.5$.

D.4 Calibration of the Short-Rate Model

Short rate dynamics are given by

$$dr_t = \alpha_r(\theta_r - r_t)dt + \sigma_r dW_t^r, \tag{IA.13}$$

where r_t is the short rate at time t, W_t^r is a standard Brownian motion, $\alpha_r > 0$ the speed of mean reversion, $\sigma_r > 0$ the volatility, and θ_r the level of mean reversion. Under the assumption of arbitrage-free interest rates, Equation (IA.13) 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

$$(1+r_{f,\tau}(t))^{-\tau} = A(\tau)e\left[-B(\tau)r(t)\right], \tag{IA.14}$$

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 $r_{f,\tau}(t)$ 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.[49] 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

D.5 Calibration of the Financial Market Model

Spreads for government and corporate bonds are modeled by truncated Ornstein-Uhlenbeck processes, such that

$$s^j(t) = \max\left(k^j(\overline{s}^j - s^j(t))dt + \sigma^j dW^j(t)\right)^+ \tag{IA.15}$$

describes the evolution of a bond class j's spread, and $\{r_{f,\tau}(t)+s^j(t)\}_{\tau\geq 0}$ is its term structure at time t. Together with a bond's modified duration, the term structure determines a bond's fair value.

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 take different inflation (expectations) between the EU and U.S. into account, we calculate bond spreads with respect to the yield of U.S. treasuries with a maturity of 10 years (obtained from

[49] 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*.

FRED St. Louis).[50] 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.6 describes the sample of bond spreads. Note that we retrieve bond rates (and spreads) for maturities 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. Since we assume the same spread for each maturity, we calibrate the spread process

$$s^j(t) = k^j(\bar{s}^j - s^j(t))dt + \sigma^j dW^j(t) \tag{IA.16}$$

for the average spread across maturities in the case of government bonds. Parameter estimates are based on Maximum-Likelihood and reported in Table IA.6. We do not allow bond rates to fall below German government bond rates (accounting for their status as de-facto risk-free rates) and, thus, truncate them in simulations such that $s^j(t) = \max\big(0, k^j(\bar{s}^j - s^j(t))dt + \sigma^j dW^j(t)\big)$.

Table IA.6. 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. Sovereign 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.7 reports the descriptive statistics for monthly log-returns. We calibrate the GBM drift and volatility with Maximum-Likelihood estimates for monthly log-returns, that are also reported in Table IA.7. 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.

[50]Results are similar if we take German government bond rates instead.

Table IA.7. 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 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.8 reports the correlation coefficients based on monthly residuals after fitting bond spreads, stock and real estate returns.

Table IA.8. 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), Netherlands (NL), Italy (IT), 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

E Additional Model Results

Figure IA.13. Fire Sale Costs and Price Impact.
The figure depicts the fire sale cost of asset sales relative to previous year's total equity capital (left axis) and the price impact (right axis) as defined in Equation (9) for the baseline calibration. The figure shows the median and 25th/75th percentile for each year.

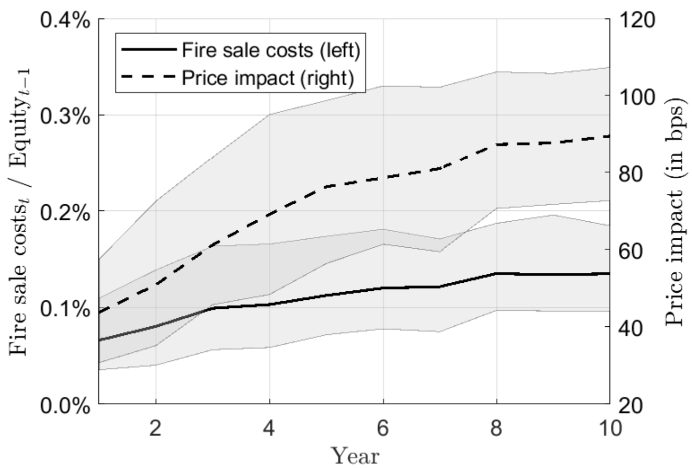
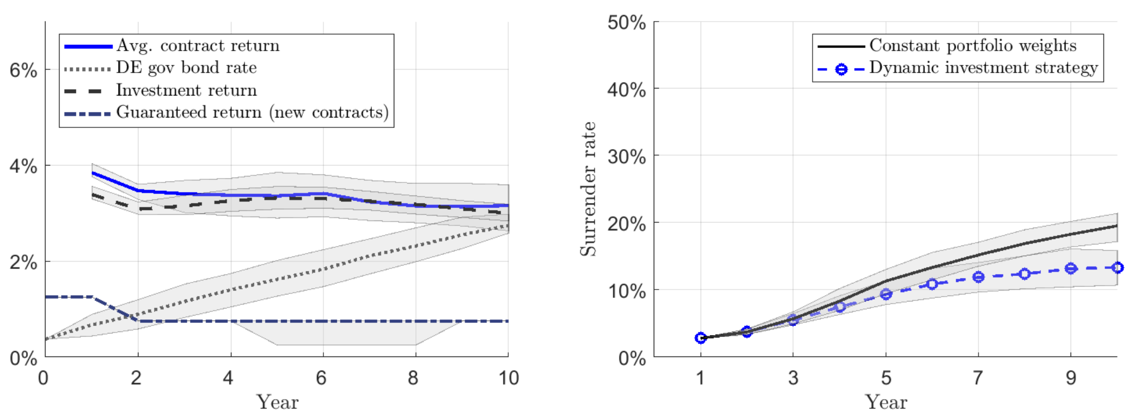


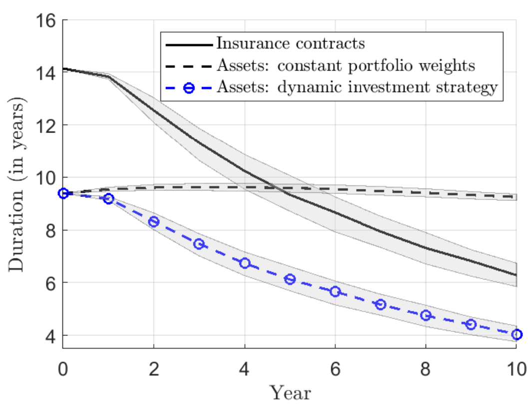
Figure IA.14. Counterfactual Calibration: Interest Rate, Contract Return, and Surrender Rate with Dynamic Investment Strategy.
Figure (a) depicts the simulated contract return for an average cohort, 10-year German government bond rate, the insurer's investment return, and the guaranteed return for new contracts (median and 25th / 75th percentiles) assuming that the insurer follows the dynamic investment strategy. Figure (b) depicts the median and 25th and 75th percentiles of the share of surrendered contracts for the baseline calibration (with constant asset portfolio weights) and the counterfactual calibration (with dynamic investment strategy).



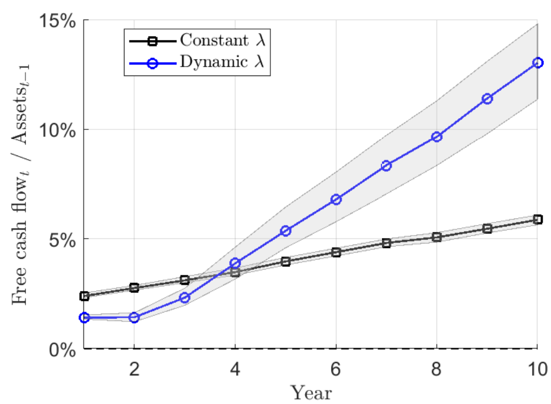
(a) Interest rate and returns. (b) Surrender rate.

Figure IA.15. 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.