Life Insurance Convexity *

Christian Kubitza†, Nicolaus Grochola‡, Helmut Gründl§

This version: March 22, 2022
Click here for the most recent version.

Abstract

Life insurers sell savings contracts with surrender options, allowing policyholders to prematurely withdraw guaranteed surrender values. Surrender options move toward the money when interest rates rise. Hence, higher interest rates raise surrender rates, as we document for the German life insurance sector. Using a calibrated model, we estimate that surrender options would force insurers to sell up to 2% of their investments during an enduring interest rate rise of 25 bps per annum. The resulting price impact depends on insurers' investment behavior. Forced asset sales are amplified by insurers' long-term investments but mitigated by reducing the guarantees on surrender values.

Keywords: Life Insurance; Liquidity Risk; Interest Rates; Fire Sales; Systemic Risk
JEL Classification: G22; E52; G32; G28

---

*We are grateful for comments and suggestions by Kartik Anand, Mark Browne, Martin Brown, Nuri Ersahin, Chuck Fang, Till Förstemann, Irina Gemmo, Robin Greenwood, Johan Hombert, Tobias Huber, Jonas Jahnert, Pab Jotikasthira, Nikunj Kapadia, Luc Laeven, Yuliyan Mitkov, Axel Möhlmann, Simon Rother, Casey Rothschild, Jochen Russ, Eva Schliephake, Isabel Schnabel, Philipp Scharner, Hato Schmeiser, Alexandros Vardoulakis, and participants at the 2021 ARIA, 2021 SGF, 2021 EGRIE, 2021 DVfVW, 2021 AEA, and 2020 Paris December Finance meetings, 8th Bundesbank-CFS-ECB Workshop on Macro and Finance, 2017 IAALS Colloquium, and seminars at Deutsche Bundesbank, ECB, EIOPA, University of Bonn, St. John's University New York, UMASS Isenberg School of Management, and Goethe University Frankfurt. This version supersedes the previously circulating paper "Rising interest rates, lapse risk, and the stability of life insurers", that was co-authored by Elia Berdin. We thank Elia for his support during the first phase of this project. Kubitza gratefully acknowledges funding by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany's Excellence Strategy (EXC 2126/1 – 390838866). Grochola and Gründl gratefully acknowledge funding by the International Center for Insurance Regulation.

†Corresponding author, University of Bonn, Institute of Finance and Statistics, Adenauerallee 24-42, 53113 Bonn, Germany. christian.kubitza@uni-bonn.de.

‡Goethe University Frankfurt, International Center for Insurance Regulation, Germany. grochola@finance.uni-frankfurt.de.

§Goethe University Frankfurt, International Center for Insurance Regulation, Germany. gruendl@finance.uni-frankfurt.de.

"[...] 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) and their products account for more than 20% of households' assets.[2] A major role of life insurers is to facilitate household saving by selling long-term savings contracts with minimum return guarantees. These contracts typically entail surrender options, which allow policyholders to terminate the contract before its maturity and receive an ex ante guaranteed surrender value. When interest rates rise, surrender options move toward the money. This paper quantifies the resulting effects on the insurance sector's liquidity risk and spillovers to financial markets.

First, we provide empirical evidence for a causal effect of interest rates on life insurance surrender. Our estimate implies that a 1 percentage point (ppt) increase in the government bond yield on average leads to a 17.5 basis point (bp) increase in the surrender rate, i.e., in the share of life insurance contracts surrendered. Thus, the expected lifetime and, hence, the interest rate duration of life insurance contracts decreases with rising interest rates, a characteristic of fixed-income products often called *convexity*. Second, we estimate a structural model for policyholders' surrender decisions and embed it into a granular model of a stochastic financial market and a representative life insurer's cash flows. Numerical simulations of the model show that increased surrender rates during an enduring interest rate rise of 25 bps per annum would force insurers to sell nearly 2% of their assets annually. Due to insurers' significant price impact in financial markets (e.g., Ellul et al., 2011; Kubitza, 2021), surrender-driven asset sales may significantly reduce asset prices, by up to 40 bps in

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

our model. Third, we use our model to explore the determinants of forced asset sales. Important determinants are the long duration of insurers' investments, which boosts the value of surrender options when interest rates rise, and the guarantee on surrender values, which amplifies the interest rate sensitivity of surrender incentives. Insurers' investment strategy has a small effect on the total volume of asset sales but a large effect on their timing and their distribution across bond maturities.

Policymakers are increasingly concerned about the liquidity risk resulting from surrender options in life insurance, especially in an environment with increasing interest rates (e.g., Cancryn, Adam, 2015; ESRB, 2015; ECB, 2017; Deutsche Bundesbank, 2018; ESRB, 2020; IMF, 2021; Moody's Investors Service, 2021).[3] For example, both the European and U.S. supervisor, the European Insurance and Occupational Pensions Authority (EIOPA) and the National Association of Insurance Commissioners (NAIC), are exploring the risks posed by rising interest rates and surrenders and the implications of life insurers' asset sales (see EIOPA, 2018, 2019 and NAIC, 2021). Indeed, surrender payouts are economically significant. For example, European life insurers paid out EUR 362 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 impact of surrenders on life insurers' liquidity risk and its interaction with the level of interest rates.

We address this gap using the German life insurance market as a laboratory. German life insurers jointly collect EUR 150 billion annually in insurance premiums (EIOPA, 2020). The most popular life insurance contracts in Germany are participating contracts, whose cash an insurer invests in a single portfolio of assets. By default, these contracts include surrender options with ex ante guaranteed surrender values. When rising interest rates

[3] (Funding) Liquidity risk is the risk that a financial institution becomes "unable to settle obligations with immediacy" (Drehmann and Nikolaou, 2010, p.1). We focus on surrenders and their impact on insurers' free cash flow as a main determinant of life insurers' liquidity risk and, if the free cash flow becomes negative, a main driver of asset sales. This focus on surrender-driven liquidity risk in life insurance is shared by policymakers, such as the European Systemic Risk Board (ESRB, 2020, p.6) and the European Insurance and Occupational Pensions Authority (EIOPA, 2021, p.10-11).

[4] In 2019, U.S. life insurers paid out $345 billion, which corresponds to more than 40% of their net premium income (NAIC, 2020a).

depress market prices, surrendering becomes more attractive because it allows policyholders to exchange the claim on insurers' (depreciated) 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 insurer-level 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 for long-term financial products.

The OLS estimate implies that a 1 ppt increase in the interest rate is associated on average with a 17.5 bps increase in the surrender rate when controlling for time-invariant heterogeneity across insurers, macroeconomic conditions, and the composition of the life insurance business. The economic magnitude is large: we estimate that a 1 standard deviation increase in interest rates roughly corresponds to an increase in aggregate surrender payouts of EUR 1.6 billion in Germany. To focus on the economic mechanism, we explore the interaction between interest rates and the guaranteed minimum return on life insurance contracts. The larger the guaranteed return, the less interest-rate-sensitive are surrender incentives. Consistent with this rationale, we find 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 a younger insurance portfolio.[5] Comparing the sensitivity across insurers allows us to include time fixed effects, which absorb any aggregate shocks that might correlate with both interest rates and surrender rates, such as insurers' investment activities.

To further strengthen the identification, we exploit the U.S. federal funds rate as an instrumental variable for German government bond rates. The federal funds rate reflects the Fed's monetary policy stance. It is significantly positively correlated with the German government bond rate, consistent with an international bond market channel. Since German life insurers hold very little U.S. bonds, the impact of the German life insurance market on

[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.

U.S. monetary policy is plausibly negligible, which supports the exclusion restriction. Using this alternative identification strategy has a modest impact on the coefficients and their significance, consistent with a causal effect of interest rates on surrenders.

Motivated by this evidence, the second part of this paper quantifies the risk of surrender-driven 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. The calibration accounts for 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 and other investments, and accounts for 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 "interest rate rise" paths, the average annual interest rate change is 25 bps, which corresponds to the 75th percentile of annual changes in the 10-year German government bond rate since 1980. The interest rate rise drives up surrender rates to close to 12% in our simulation. Associated surrender payouts drain the insurer's free cash flow and, after 7 years, force the insurer to sell assets. The longer the interest rate rise lasts, the more assets the insurer has to sell each year. Total sales reach nearly 3% of total assets after 10 years of rising interest rates, with nearly two-thirds of these sales driven by surrenders and the remaining part driven by portfolio rebalancing. Due to the systematic nature of an interest rate rise, this effect on insurers' investment behavior is likely to be similar across life insurers that offer similar contracts.

To provide an estimate of the volume of aggregate asset sales, we scale our simulations to the aggregate size of European life insurers that offer similar contracts with surrender options. Following prior literature in calibrating insurers' price impact (specifically, Greenwood et al., 2015), the simulations imply that surrender-driven asset sales reduce asset prices by up to 40 bps. This magnitude is plausible compared to empirical studies on fire sales by insurers, and it is 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 rationale for policymakers' effort to closely monitor the provision of surrender options.

In counterfactual calibrations, we explore the sensitivity of our results. We find that the duration of the insurer's asset investments is an important determinant of the interest rate sensitivity of surrender-driven asset sales. A long duration isolates the insurer's investment return at book values from interest rate changes, which is important since, by regulation, the book value investment return determines the contract return to policyholders. The longer the investments' duration, the longer it takes contract returns to increase after interest rates have started to rise. This divergence of contract returns and market interest rates strengthens surrender incentives. Consistent with this mechanism, in our model, an increase in asset duration from below 8 to 12 years relates to an increase in the total volume of asset sales from below 1% to more than 2.5% of total investments in an average year.

In the baseline model calibration, we assume that the insurer keeps constant portfolio weights across assets with different durations. However, when rising interest rates reduce the duration of insurance contracts, insurers are likely to match this dynamic by reducing the duration of their investments (Domanski et al., 2015). In a counterfactual calibration, we implement such duration matching. A lower asset duration strengthens the pass-through of interest rate changes to contract returns and, thereby, weakens surrender incentives. Consequently, we find that surrender rates are lower under the dynamic investment strategy. However, duration matching itself motivates the insurer to sell a large fraction of its long-term investments when interest rates rise to reduce the overall asset duration. As a result, the volume of total asset sales and their price impact are only slightly smaller than those in the baseline calibration with constant portfolio weights. Nonetheless, the timing and compo-

[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 nonfinancial firms, respectively.

sition of asset sales change substantially. In the baseline calibration, the insurer sells mostly short-term bonds to keep portfolio weights constant, since these bonds gain in value relative to long-term bonds when interest rates rise. Instead, under duration matching, the insurer sells mostly long-term bonds to reduce the investments' overall duration. Thus, insurers' investment strategy has important consequences for their impact on the slope of the yield curve. With constant portfolio weights, asset sales increase *short-term* relative to long-term yields, which flattens the yield curve. When matching asset and liability duration, asset sales increase *long-term* relative to short-term yields, which steepens the yield curve.

Finally, we discuss how to reduce the interest rate sensitivity of surrender rates. In a counterfactual calibration, we show that reducing the guarantees on surrender values by adjusting surrender values to the current level of interest rates can reduce surrender rates and insurers' price impact during an interest rate rise. We argue that such market value adjustments can be a viable policy tool, and discuss the potential advantages over other considered tools, namely the suspension of surrender payouts and large surrender penalties.

Liquidity risk has long been acknowledged as an important driver of fragility in the financial sector. 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). Whereas the surrender options embedded in most life insurance contracts resemble withdrawal options of demand-deposit contracts, life insurers differ from other financial institutions in many aspects, such as their regulation and offering of long-term guarantees (Koijen and Yogo, 2021; Ellul et al., 2021). The significant size of life insurers and their pivotal role in fixed-income markets (Ellul et al., 2011; IMF, 2016; Kubitza, 2021; Koijen and Yogo, 2022) warrant a detailed understanding of their liquidity risk. However, while a growing literature studies how regulatory frictions shape insurers' investment behavior and funding structure (Becker and Ivashina, 2015; Koijen and Yogo, 2016; Sen, 2020; Becker et al., 2021), less is known about the role of surrender rates in life insurers' liquidity risk.[7]

[7] Whereas surrender options expose life insurers to liquidity risk, life insurers may also profit from policyholders' behavioral biases about their need to surrender a contract (Gottlieb and Smetters, 2021).

In theory, surrender options move toward the money when interest rates increase (Albizzati and Geman, 1994; Förstemann, 2019; Chang and Schmeiser, 2021). 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) estimates the potential asset sales that would result from surrender by all policyholders after a sufficiently large and immediate hike in interest rates that reduces an insurer's assets' market value below surrender values. Complementing previous studies, we use an empirically calibrated, structural model of policyholders' surrender decisions, embedded in a dynamic model of insurance cash flows, and estimate the effects of a plausible increase in interest rates. We use this model to focus on the interaction among market interest rates, insurers' investments, surrender incentives, and asset sales.

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 prepayments less favorable and, thereby, increases the duration of mortgage-backed securities, amplifying interest rate volatility (Hanson, 2014). The convexity of life insurance is important for understanding life insurance markets because it provides a possible explanation for why life insurers in practice maintain large negative duration gaps, i.e., longer-dated liabilities than assets (e.g., IMF, 2017).

Our results emphasize the role of insurers' long-dated asset investments in liquidity risk by widening the gap between guaranteed surrender values and the value of insurers' investments when interest rates rise, amplifying surrender rates when interest rates rise. This result complements previous literature that highlights the positive role of long-dated asset investment in facilitating intercohort risk sharing (Hombert and Lyonnet, 2021; 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' impact on asset prices. 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. (2021), 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. (2021)'s model in particular, in which life insurers de-risk by selling illiquid bonds and, thereby, reduce capital requirements. In contrast, surrendering policyholders directly force asset sales 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 their price impact. Section 4 discusses empirical predictions and policy implications, and Section 5 concludes the paper.

1 Institutional Background and Anecdotal Evidence

1.1 Life Insurance Contracts and Surrender Options

Life insurers massively sell savings contracts, which policyholders can convert into a lump sum payout or a stream of annuity payments at retirement. Before retirement, policyholders pay periodic premiums, which are invested by the insurer. Most life insurance contracts in Europe delegate investment decisions to the insurer, which pools the insurance premiums and invests them in a joint portfolio (so-called *participating contracts*).[8]

[8] More than 60% of European (and nearly 90% of German) life insurance reserves are for participating contracts (EIOPA, 2020). Savings contracts in U.S. life insurance exhibit a stronger focus on nonparticipating policies, which allow policyholders to choose investment strategies (Koijen and Yogo, 2021).

In total, 88% of European life insurance reserves include a surrender option, which is the option to terminate a contract before maturity and receive the contract's surrender value (EIOPA, 2019). Among participating contracts with a surrender option, the surrender value is ex ante guaranteed in nearly all cases (namely, for 91% of reserves; EIOPA, 2019).[9] Due to the prevalence of participating contracts, the overall share of life insurance with a surrender option and guaranteed surrender value is substantial and corresponds to approximately 60% of European life insurance reserves (nearly EUR 5 trillion in 2019; EIOPA, 2020).

Disincentives to surrender can result from penalties imposed by insurers and from the loss of the tax advantages of life insurance products. Moreover, 27% of European life insurance reserves carry a tax disincentive, while 17% carry surrender penalties (EIOPA, 2019). Less than 10% impose surrender penalties of 15% or more (ESRB, 2015). Consistent with this evidence, according to anecdotal information from the German insurance industry, surrender penalties in Germany are very small (on the order of 2.5% of surrender values) since they are supposed to only cover administrative expenses. Hence, surrender disincentives are not widespread, and if they exist, they are small.

Within Europe, the provision of surrender options and guaranteed surrender values is especially pronounced in Germany (EIOPA, 2019). The guaranteed surrender value of German participating contracts is mandated to equal 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.

1.2 Economic Significance of Surrender Options

We explore the size of surrender payouts by life insurers drawing on data retrieved from EIOPA (2020) and NAIC (2020a) on life insurers' cash flows and assets at the country level. Total surrender payouts in 2019 were EUR 362 billion in Europe, of which EUR 21.5 billion

[9] U.S. life insurance contracts also include surrender options with guaranteed surrender values, as we describe in Appendix A.

were in Germany, and EUR 308 billion in the U.S. (equivalently, $345 billion). Surrender payouts 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. The ratio of surrender payouts to life insurance premiums has a similar size. Even when accounting for other cash flows (insurers' investment income, insurance benefits, and expenses), surrender payouts remain a significant share of the resulting net cash flow, for example, 24% in Germany (BaFin, 2019). Thus, surrender payouts are a significant determinant of life insurers' liquidity.

There is substantial variation in the relative size of surrender payouts across countries, as we show in Figure 1. An important determinant of this variation is the type of insurance contract: we find that variation in the share of nonparticipating contracts (relative to all life insurance reserves) explains 27% of the variation in surrender payouts relative to premiums across EU countries in 2019 (the correlation is 52%). Thus, although nonparticipating 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). Based on EIOPA (2020), we estimate that approximately 42% of European life insurers' assets are liquid, with wide variation ranging from 20% (Germany) to 85% (Hungary).[10] Surrender payouts correspond to approximately 15% of these liquid assets. Thus, the size of surrender payouts is economically significant, relative not only to insurers' cash flows but also to their liquid asset holdings.

[10] We define liquid assets as the sum of cash and deposits, common equity, equity and money market mutual funds, and central government, treasury, and central bank bonds. We include assets held for unit- or index-linked insurance because they are included in reported surrender payouts.

1.3 Anecdotal Evidence

Anecdotal evidence emphasizes the impact of interest rates on life insurance surrender and liquidity. For example, U.S. surrender rates increased sharply from roughly 3% in 1951 to 12% in 1985 in response to a rise in market interest rates in the late 1970s and early 1980s (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 run-like situations. For example, upon large investments in illiquid assets by U.S. insurers, a massive fraction of policyholders surrendered their contracts in the early 1990s, which resulted in the failure of seven U.S. life insurers (DeAngelo et al., 1994; Jackson and Symons, 1999; Brennan et al., 2013). These insurers heavily sold guaranteed investment contracts (GICs), which are savings contracts with financial guarantees resembling modern savings contracts. The surrender of these GICs significantly contributed to the life insurers' failure (Brewer and Strahan, 1993). Similarly, in 1999, rising interest rates sparked mass surrenders of GICs sold by *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 1997–1998. As interest rates sharply rose (by approximately 4 ppt for 5-year government bonds within a few months), annualized surrender rates increased from 11% to 54.2% for long-term savings contracts, and life insurers' gross premium income fell by 26%. Life insurers were forced to liquidate assets, and approximately one-third of Korean life insurers exited the market (Geneva Association, 2012).

2 Empirical Analysis

This section provides empirical evidence that high market interest rates boost life insurance surrender, consistent with policyholders maximizing yield.

2.1 Data and Empirical Specification

We use the German life insurance market as an empirical laboratory. Life insurance demand in Germany is close to that in 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.

BaFin, the German financial supervisory authority, annually publishes the *Erstversicherungsstatistik* (i.e., *statistics on primary insurers*), a dataset that contains information on surrender rates, premium income, investment return, and portfolio size for each German life insurer (excluding reinsurers). We digitize the data for 1995 to 2010, which are available only in print or pdf format. Since a common identifier for insurers is missing in the data, we match insurers by hand over time, resulting in a survivorship-bias-free panel from 1995 to 2019. The panel structure allows us to include insurer fixed effects in regressions, controlling for time-invariant insurer characteristics.

An insurer's annual surrender rate is the fraction of life insurance contracts surrendered weighted by the volume of insurance in force. BaFin reports this surrender rate starting in 2016, while prior to 2016, it is divided into an early surrender rate (surrender rate of new business) and a late surrender rate (other surrender as a fraction of the average contract portfolio in a given year). For these years, we define an insurer's overall surrender rate as the weighted average of the early and late surrender rate, using the previous year's insurance in force (as described in Appendix B).

The final sample of insurer-level variables starts in 1996. All variables are winsorized at the 1% and 99% levels. The sample comprises 159 life insurers and accounts for EUR 71 billion in insurance premiums in an average year. Aggregate life insurance market dynamics are relatively stable over time. There is a slight increase in new insurance business and premiums and a slight decrease in the number of insurers (see Figure 2 a). The average

[11] For example, life insurance premiums per capita (alternatively, relative to the gross domestic product) were $1,161 (2.41%) in Germany, $1,978 (4.6%) in advanced Europe and Middle East Asia, and $1,774 (2.91%) in North America in 2019 (Swiss Re Institute, 2019).

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 average surrender rate is lower than typical withdrawal rates for other savings products, such as time deposits in banking. For example, for a sample of Greek banks, Artavanis et al. (2019) document that, in calm times, 15% of time deposits are withdrawn before maturity annually.

The main explanatory variable in our regressions is the level of market interest rates. We use the annualized yield of German government bonds with a residual maturity of 10 years ("German government bond rate" in the following) as a proxy since it is a widely used benchmark and available with a long history.[12] Lagged government bond rates capture market conditions prior to surrender decisions (contemporaneous bond rates might be affected by surrender-driven variation in insurers' bond demand). The 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

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

where $\text{Interest rate}_{t-1}$ is the 10-year German government bond rate, $X_{i,t-1}$ are insurer-level control variables, Y_{t-1} are macroeconomic control variables, and u_i are insurer fixed effects. α estimates the effect of interest rates on surrender rates. We expect that $\alpha > 0$ since higher interest rates increase the exercise value of surrender options. Consistent with this hypothesis and the model specification, the binscatter plot in Figure 2 (b) suggests a linear relationship between surrender rates and interest rates.

We control for the potential impact of the composition of an insurer's contract portfolio on surrender rates in two ways. First, $X_{i,t-1}$ includes the ratio of the volume of new insurance business relative to that of total insurance business at year-end at the insurer level (retrieved from the Erstversicherungsstatistik). Second, Y_{t-1} includes the log of total new

[12] Our results are robust to using other maturities, e.g., 20 years.

life insurance contracts, capturing aggregate variation in insurance demand, and the share of new term life contracts, capturing variation in the composition of life insurance business (both retrieved from the German association of insurers, GDV). Moreover, we control for an insurer's lagged investment return (retrieved from the Erstversicherungsstatistik), capturing potential performance-driven surrender incentives.

Since the main explanatory variable is at the year level, we cannot simultaneously estimate its coefficient and include year fixed effects. Instead, we control for 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 (based on Laeven and Valencia, 2018). In additional specifications, we interact the German government bond rate with insurer characteristics, which allows us to additionally include year fixed effects. In particular, we use the guaranteed minimum contract return ("Guaranteed return") for new insurance business, reflected by the technical discount rate for German life insurance contracts.[13]

Despite including a wide array of control variables, there are two important concerns regarding the identification of α in Equation (1). First, unobserved variation in the economic environment can affect both interest rates and surrender rates. Second, surrender rates can affect life insurers' investment behavior and, thereby, interest rates. Indeed, German life insurers hold approximately 6% of outstanding German government debt securities.[14]

We address these identification concerns in two steps. First, we include time fixed effects in specifications with insurer-by-time-level interaction terms, which absorb variation in insurers' bond demand. Second, we improve causal identification by using the U.S. federal funds rate (which captures variation in U.S. monetary policy) as an instrumental variable for German government bond rates.

[13]See Eling and Holder (2013) for a discussion on the relation between the technical discount rate (called "Höchstrechnungszins") and guaranteed minimum return.

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

Intuitively, tighter U.S. monetary policy (i.e., a higher federal funds rate) increases U.S. treasury rates, which affect German government bond rates through an international arbitrage channel. Consistent with this intuition, the coefficient on the federal funds rate is significantly positive in the first-stage regressions. The F statistic in the first stage is well above the critical value of 10, alleviating the concern that the instrument is weak. The exclusion restriction requires that U.S. monetary policy is uncorrelated with any determinant of German surrender rates other than the German government bond rate. It is supported by two observations. First, German life insurers' investments in U.S. bonds are negligible.[15] Thus, it is plausible to assume that German life insurers' bond demand has a negligible impact on U.S. monetary policy. Even in the presence of this channel, surrender-driven bond sales would drive up bond yields and, thus, likely exert downward pressure on the federal funds rate, making our estimates more conservative. Second, the U.S. federal funds rate does not significantly correlate with the surrender rate when controlling for the German government bond rate (see Appendix B). This observation supports the assumption that the surrender rate and the instrument are linked only through the German government bond rate. Moreover, we include a large set of macroeconomic control variables, which additionally alleviate the concern that macroeconomic trends might simultaneously correlate with both U.S. monetary policy and German surrender rates.

2.2 Results

Consistent with the hypothesis that higher interest rates boost surrender rates, the first column of Table 2 documents a highly significant and positive coefficient on the German government bond rate in the baseline specification (1). A one standard deviation increase in the interest rate relates to an increase in the surrender rate by approximately 0.13 standard deviations (33.5 bps). A back-of-the-envelope-calculation shows that this magnitude is

[15] German life insurers held EUR 723.8 million in U.S. treasuries as of 2018 (Source: EIOPA (2020)), compared to EUR 10,789 billion in publicly held and marketable U.S. government bills, notes, and bonds outstanding in 2018 Q1 (Source: *U.S. Treasury's "Monthly statement of the public debt of the United States"*).

economically significant: it corresponds to an increase of approximately EUR 1.6 billion in aggregate surrender payouts in Germany, using the volume of German life insurance in 2019 as a benchmark.[16]

To reveal the economic mechanism driving the correlation between surrender rates and interest rates, we examine the interaction between interest rates and contracts' guaranteed minimum return. If policyholders surrender to maximize yield, a higher guaranteed return will reduce their sensitivity to market interest rates, consistent with our model (see Section 3.1). Since we only observe the guaranteed return for new insurance contracts, in column (2), we focus on insurers with a large share of new insurance business (insurer-year observations with the 50% largest share of new business). Consistent with the hypothesis of yield-maximizing policyholders, we find a large and significantly negative coefficient on the interaction between the German government bond rate and contracts' guaranteed return. The estimate suggests that a guaranteed return of approximately 3% would make policyholders insensitive to interest rate changes, which corresponds to the upper tercile of guaranteed returns in our sample.

Since the guaranteed return applies only to new insurance contracts, its effect on surrender rates' interest rate sensitivity should be stronger for insurers with a larger share of new business. To test this hypothesis, we include a triple-interaction term of interest rates, the guaranteed return, and an insurer's share of new business, which we estimate for the full sample. Importantly, this specification allows us to include not only insurer but also year fixed effects, which absorb any unobserved aggregate trends, e.g., in insurance regulation or the macroeconomic environment. In column (3), we find that the coefficient on the triple-interaction term is significantly negative. Thus, the negative impact of guaranteed returns on the interest rate sensitivity of surrender rates significantly increases with the share of new

[16] The annual ratio of aggregate surrender payouts to the aggregate volume of insurance surrendered ranges from 14.1% to 17%, with an average of 15.5% according to BaFin's *Erstversicherungsstatistik* from 2011 to 2019. Using the aggregate volume of insurance in Germany at year-begin 2019 (EUR 3,126 billion), a one-standard-deviation increase in the interest rate approximately corresponds to an increase in surrender payouts of $0.00335 \times 0.155 \times 3,126 \approx$ EUR 1.6 billion.

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. We find that this alternative identification strategy results in similar point estimates and statistical significance of coefficients, consistent with a causal effect of interest rates on surrender rates.

We provide additional results in Appendix B.2. First, we show that the results are similar when using the 10-year U.S. treasury rate as an alternative instrument. This result supports the argument that variation in the U.S. federal funds rate transmits 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 insignificant (with an absolute value of the t-statistic below 0.05) once controlling for the German government bonds rate. This result supports the identifying assumption that there is no alternative channel through which the U.S. federal funds rate affects German surrender rates.

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

3 Surrender Options and Financial Fragility

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

3.1 Model

We first propose and estimate a model for the surrender of life insurance savings contracts. Second, we embed this model into a broader setting that captures the balance sheet and cash flow dynamics of a representative German life insurer that sells savings contracts with surrender options and minimum guaranteed returns, calibrated to end-of-2015.[17] Below, we describe the defining ingredients of the model and relegate more details to Online Appendix C, in which we also provide an overview of the model components and their interactions.

3.1.1 Savings Contracts. We model the primary features of life insurance savings contracts. Specifically, contracts are long term and annually return the maximum of a (at contract origination) fixed guaranteed minimum return and the insurer's investment return. For tractability, we focus on contracts' savings phase and exclude mortality risks. Policyholders annually invest the premium $P > 0$ and receive a lump-sum payout at contract maturity.[18]

Each year, each policyholder may surrender her contract, upon which the insurer pays out the contract's cash value, which is the contract return accumulated since contract origination, less a surrender penalty. Specifically, the total cash value of policyholder cohort h at year-end

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

[18] Life insurance contracts typically allow policyholders to transform the lump sum payout into an annuity at maturity. However, policyholders usually prefer receiving the lump sum payout, which is often referred to as the *annuity puzzle* (see, e.g., Mitchell and Moore, 1998; Brown, 2001).

$t+1$, V^h_{t+1}, evolves after contract origination h, $t+1>h$, according to

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

where N^h_t is the number of policyholders at year-end t, $\tilde{r}^h_{P,t+1}$ is the contract return credited to policyholders at year-end $t+1$, and P^h are the annual premiums paid by each policyholder to the insurer. At contract origination $t=h$, the cash value equals the total premium payments by new policyholders, $V^h_h = N^h_h \cdot P$. We assume that the number of new policyholders at contract origination h is fixed over time, $N^h_h \equiv N$. This assumption is consistent with the observation that new life insurance business in Germany remained at similar levels in recent decades (see Figure 2).[19] At contract maturity T^h, the final cash value $V^h_{T^h}$ is paid out to the remaining policyholders.

Policyholder dynamics are governed by the surrender rate λ^h_{t+1}, which is the fraction of the previous year's policyholders that surrender in year $t+1$, $\lambda^h_{t+1} = \frac{N^h_t - N^h_{t+1}}{N^h_t}$. The surrender rate is endogenously determined, as described in the next section. The surrender value of contracts in cohort h, SV^h_t, is determined at year-end t and paid out upon surrender in $t+1$. It equals the lagged cash value V^h_t less the surrender penalty $1-\vartheta$, $\vartheta \in (0,1)$, such that $SV^h_t = \vartheta \cdot V^h_t$.

The annual contract return is given by

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

r^h_G is a cohort h's guaranteed minimum rate of return, which is fixed at contract origination h for the entire contract life. Following German regulation, we assume that r^h_G is annually adjusted (for new cohorts) and tracks 60% of the 10-year moving average of 10-year German

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

government bond rates in 50 bps steps (Eling and Holder, 2013).[20]

We focus on participating contracts due to their dominance in the European life insurance market (see Section 1.1). Thus, premiums are jointly invested at the insurer level. Policyholders receive a fraction $\xi \in (0, 1)$ of the insurer's total investment income R^{inv}_{t+1} allocated relative to cash values (if it exceeds the guaranteed return r^h_G),

$$\tilde{r}^*_{t+1} = \xi \frac{R^{inv}_{t+1}}{\sum_h V^h_t}. \tag{4}$$

The investment income R^{inv}_{t+1} is determined by historical cost accounting. It is the sum of bond coupon payments, stock dividends, and rents less depreciations.[21] Therefore, it critically hinges on the insurer's investment allocation, which we describe 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 (a) market interest rates, (b) contract return, and (c) contract age.[22]

We consider a policyholder at year-begin t who has started investing in a savings contract at year-end h, $h < t$. Her current cash value is $v^h_{t-1} = V^h_{t-1}/N^h_{t-1}$, and the surrender value is $sv^h_{t-1} = SV^h_{t-1}/N^h_{t-1}$, both based on year-end $t-1$. While we do not explicitly model fees that cover administrative costs in the insurer's cash flow (since fees and administrative costs would net out), fees are a potentially important determinant of surrender decisions. Without loss of generality, we assume that policyholders pay fees to cover administrative costs at the earlier of the surrender or the maturity date. Cumulative fees are the fraction

[20] Regulators in many countries set maximum levels for guaranteed returns that depend on long-term interest rate averages (Grosen and Jorgensen, 2002). German insurers have typically offered guaranteed returns equal to this maximum level. German law specified 60% of the 10-year yield on AAA-rated European government bonds as the maximum guaranteed return until 2015 (§65 Insurance Supervision Act). Since 2015 the calculation of this cap is not specified (§88 Insurance Supervision Act). However, the German regulator has not been deviating significantly from the historical rule. For example, our model predicts that the guaranteed return would be lowered in 2017 if interest rates were not increasing substantially, which matches the realized (maximum) guaranteed return.

[21] Note that the investment income R^{inv}_{t+1} does not consider unrealized market value gains. We abstract from insurers' active reserve management, which is analyzed by Hombert and Lyonnet (2021).

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

$1 - e^{-c(t-h-1)}$ of the contract payout, where $c(\cdot)$ is a nonnegative function that increases with contract age $t - (h+1)$ at year-begin t. 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 net utility $e^{\mathcal{L}}$ proportional to the surrender value, which is the utility of satisfying liquidity needs, e.g., arising from unemployment, medical expenses, or new consumption opportunities, net of transaction costs, such as the loss of the option to convert the contract into an annuity at maturity. We allow $\mathcal{L}$ to vary across policyholders, both across and within cohorts, reflecting differences in liquidity needs and transaction costs. The net surrender value is then given by $sv_{t-1}^h \cdot e^{\mathcal{L}-c(t-(h+1))}$.

A policyholder surrenders her contract if the net surrender value exceeds the value of holding on to the policy, m_{t-1}^h, net of fees at contract maturity, $1 - e^{-c(T^h-h)}$, i.e., if[23]

$$sv_{t-1}^h \cdot e^{\mathcal{L}-c(t-h-1)} > m_{t-1}^h \cdot e^{-c(T^h-h)}. \tag{5}$$

To compute m_{t-1}^h, we assume that policyholders extrapolate contract returns using the most recent contract return and discount with the German government bond rate, $r_{f,t-1,T^h-(t-1)}$, at year-end $t-1$ with remaining time to maturity $T^h - (t-1)$, which implies that

$$m_{t-1}^h = v_{t-1}^h \left(\frac{1 + \tilde{r}_{P,t-1}^h}{1 + r_{f,t-1,T^h-(t-1)}} \right)^{T^h-(t-1)}. \tag{6}$$

This assumption is consistent with anecdotal evidence that life insurers mainly compete over realized contract returns in practice.[24] The surrender condition in Equation (5) is then

[23] We emphasize that our model does not require policyholders to be rational or risk-neutral (as, e.g., in Förstemann, 2019). Instead, it allows policyholders to display, e.g., behavioral biases to the extent that they affect the mean and standard deviation of $\mathcal{L}$ or the slope of $c(\cdot)$.

[24] Numerous studies document the low level of financial literacy among consumers (e.g., Lusardi and Mitchell, 2014), which Nolte and Schneider (2017) highlight as a significant determinant of surrender decisions. This evidence suggests that consumers rely on observable characteristics, such as contract returns, to evaluate contracts. Extrapolative beliefs about investment returns are common, even among professional investors such as pension funds (Andonov and Rauh, 2021).

equivalent to

$$\mathcal{L} > \log\left[\vartheta^{-1}\left(\frac{1+\tilde{r}^h_{P,t-1}}{1+r_{f,t-1,T^h-(t-1)}}\right)^{T^h-(t-1)}\right] - \Delta c_t. \tag{7}$$

The right-hand side of Equation (7) is the log of the value of holding the life insurance contract relative to its surrender value, $\log \frac{m^h_{t-1}}{sv^h_{t-1}}$, less future fees $\Delta c_t = c(T^h - h) - c(t-(h+1))$. Thus, lower future fees Δc_t reduce the incentive to surrender. Instead, fees for preceding contract years are sunk costs. Marginal fees for life insurance contracts are typically decreasing with contract age.[25] Decreasing marginal fees imply that $c(\cdot)$ is concave, $c''(\cdot) < 0$, which we parametrize as $c(x) = k \cdot \log(2+x)$ with $k > 0$ for contract age $x = t-(h+1) \geq 0$.

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

$$\lambda^h_t = 1 - \Phi\Bigg(\underbrace{\frac{-k\cdot\log(2+T^h-h)-\mu_L}{\sigma_L}}_{=\beta_0} + \underbrace{\frac{1}{\sigma_L}}_{=\beta_1}\cdot\log\frac{m^h_{t-1}}{sv^h_{t-1}} + \underbrace{\frac{k}{\sigma_L}}_{=\beta_2}\cdot\log(2+(t-(h+1)))\Bigg), \tag{8}$$

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 Erstversicherungsstatistik as described in Appendix C.1.

Figure 3 illustrates the resulting calibration. The surrender rate is monotonically de-

[25] For example, German life insurers must deduct fees evenly distributed across a contract's first 5 years (§169 Insurance Contract Act). For tractability, we assume that the cost function is twice differentiable.

clining with the contract return, reflecting higher opportunity costs of surrender. A longer remaining time to contract maturity (i.e., younger contract age) increases the interest rate sensitivity of the surrender rate, reflected by a steeper slope. 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 approximately equals 15% to 20%, which is close to the stress scenario estimated by Biagini et al. (2021) for German surrender rates.

3.1.3 Balance Sheet and Portfolio Allocation. The insurer's contract portfolio consists of several cohorts. Contracts have a fixed lifetime of $T^h - h = 40$ years at contract origination and differ according to their age, which determines the guaranteed return. The starting point of the model is the end of year $t = 0$, which we calibrate to end-of-2015. At $t = 0$, the insurer's portfolio consists of 40 cohorts. The oldest cohort $h = -39$ was sold at year-end $t = -39$ (i.e., 1976) with guaranteed return $r_G^{-39} = 3\%$, and the latest was sold in $t = 0$ (i.e., 2015) with $r_G^0 = 1.25\%$, as implied by the historical evolution of guaranteed returns in Germany.

To compute the relative size of cohorts at $t = 0$, we draw on the historical evolution of the annual volume of newly issued life insurance, average surrender rates, and contract returns in Germany and extrapolate where needed, as described in Appendix C.3. The resulting initial contract portfolio exhibits an average guaranteed return of 3.12% per contract (see Table 3), which is close to that reported by Assekurata (2016) for German life insurers in 2015 (which was 2.97%). The modified duration of the initial contract portfolio is 14.1 years, which coincides with the median duration of German life insurers' liabilities according to the German association of insurers GDV.

The insurer invests in four different types of assets: (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 weights (in market values) and interest rate durations of asset classes are calibrated based on (GDV, 2016) and (EIOPA, 2014, 2016), as detailed in Appendix C.4. The overall duration of investments is consistent with evidence from the GDV and Assekurata (2016). Fixed income is the most important asset class, with 55% of assets invested in government bonds and 34% invested in corporate bonds. The allocation of fixed-income assets across ratings is skewed toward higher-rated assets, consistent with Assekurata (2016). Bond maturities differ within the insurer's portfolio, such that within each bond category, the oldest bond is due in 1 year, the youngest government bond is due in 20 years, and the youngest corporate bond is due in 10 years, reflecting the longer duration of government bonds in insurers' portfolios. Bond coupons are based on the (government or corporate) bond yield at bond issuance.

Given the investment portfolio, the contract portfolio, and asset prices (as implied by the financial market model described in the next section) at year-end $t = 0$, we determine the insurer's leverage by matching the ratio of equity capital to total assets (both at market value) of 9%. This assumption corresponds to the ratio of equity capital to total assets of 8.8% for the average German life insurer in January 2016 (EIOPA, 2016).[26] It is also consistent with the ratio of market equity to total assets of listed European life insurers in 2015.[27] The resulting initial calibration, as reported in Table 3, closely matches the balance sheet of German life insurers in 2015. Supporting our calibration of the insurer's investment portfolio, our model predicts an average investment return of 3.45% for 2016 ($t = 1$), which closely resembles the investment return of the median German life insurer in 2016 (3.04% as reported in BaFin's Erstversicherungsstatistik).

[26] Specifically, the 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%. We follow EIOPA's approach to compute life insurance liabilities as outlined in Online Appendix C.2.

[27] 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.

Starting with the initial investment portfolio, we explore two possible investment strategies. First, in the baseline results, we assume that the insurer keeps the relative portfolio weights fixed 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 counterfactual calibration, we implement a dynamic duration matching strategy. For this purpose, we assume that the insurer targets 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, $D_0^L$is the initial liability duration, and $\tilde{D} < 1$ is the target relative duration gap. As observed in practice and implied by the calibration of our model, $D_0^L > D_0^A$. Each year, the insurer recomputes the duration of liabilities D_t^L based on the current contract portfolio. The insurer then adjusts the duration of the investment portfolio to maintain the duration gap $\tilde{D}$. For this purpose, portfolio weights are redetermined such that the duration within each asset class matches its initial duration multiplied by the scaling factor $(1 - \tilde{D}) \cdot D_t^L / D_0^A$ (as described in Appendix C.4).

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 C.5. 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 C.6.

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

Securities markets are segmented into investor clienteles (Greenwood and Vayanos, 2010; Greenwood et al., 2010; Vayanos and Vila, 2021), which implies that insurers' asset sales have a price impact.[28] This assumption is consistent with empirical evidence on insurers' price impact, e.g., in bond markets (Ellul et al., 2011; Greenwood and Vissing-Jorgensen, 2018; Bretscher et al.; Girardi et al., 2021; Jansen, 2021; Kubitza, 2021; Liu et al., 2021), and investors' price impact more generally (Koijen and Yogo, 2019). We assume segmentation into (1) short-term bonds (those with a remaining time to maturity of up to 10 years), (2) long-term bonds (those with a remaining time to maturity of more than 10 years), and (3) stocks and real estate. Then, the market value of the insurer's total assets at year-end t after realization of cash flows and readjustment of the insurer's investment portfolio is

$$A_{t+} = A_{t-} + FCF_t - FSC_t, \tag{9}$$

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

We denote the price impact of asset sales by δ and assume that $\delta = 10^{-4}$ (1 bps) per EUR 1 billion sold, following Greenwood et al. (2015). This calibration is consistent with

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

the price impact of U.S. insurers' fire sales after bond downgrades (Ellul et al., 2011). The price impact dissolves within 1 year, in line with empirical evidence that prices typically revert within 6 to 8 months (Ellul et al., 2011; Kubitza, 2021; Massa and Zhang, 2021).

To compute meaningful estimates for the insurer's price impact, we need to specify the size of its balance sheet. Policyholders with similar insurance contracts face similar surrender incentives, which implies that surrender rates are correlated across insurers. To account for this correlation, we scale our model to the volume of European participating life insurance contracts with surrender options, Ω, namely to 80% of European life insurance reserves excluding nonparticipating contracts in 2016Q3 (EUR 5.238 trillion).[29] This provides a sensible benchmark since these contracts' policyholders face common contractual features and a similar economic environment. The scaling factor is conservative for two reasons. First, insurers may also have to sell assets when nonparticipating contracts are surrendered, which we exclude because their surrender dynamics may differ from those implied by our model. Second, we are conservative in estimating the share of contracts that can be surrendered, which EIOPA (2019) reports to slightly exceed 80%.

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

$$\underbrace{\delta \cdot \Omega \cdot \max\{-(w_t^k A_{t+} - a_{t-}^k), 0\}}_{\text{Price impact}_t^k} \cdot \underbrace{\max\{-(w_t^k A_{t+} - a_{t-}^k), 0\}}_{\text{Sales}_t^k} . \tag{10}$$

The price impact reflects externalities generated by asset sales on other institutions.[30] Plug-

[29] German life insurance reserves account for approximately 19% of European life insurance reserves (EIOPA, 2020). Whereas our model is calibrated based on data from 2015, the earliest available data on European life insurance reserves under a uniform accounting regime (following the Solvency II standards) are from 2016Q3 (EIOPA, 2020). Since the volatility of European life insurance reserves over time is very low (the standard deviation of quarterly European life insurance reserves between 2016Q3 and 2018Q1 is approximately 2% relative to 2016Q3), we use the value from 2016Q3 to scale our model.

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

ging this expression into Equation (9) yields

$$A_{t+} = A_{t-} + FCF_t - \sum_{k \in \mathcal{K}} \delta \cdot \Omega \cdot \max\{-(w_t^k A_{t+} - a_{t-}^k), 0\}^2. \tag{11}$$

The insurer's previous year's asset allocation, contract portfolio, and the financial market model jointly determine A_{t-}, a_{t-}^k, and FCF_t. The investment strategy determines w_t^k (which is either fixed or varying with the duration of liabilities). δ and Ω are exogenous parameters. Given these variables, we use Equation (11) to determine the market value of total assets A_{t+}, which then determines fire sale costs and the asset allocation.[31]

Our approach to computing insurers' asset sales and price impact makes two important assumptions. First, insurers do not finance surrender payouts by taking on additional debt instead of selling assets. This assumption is motivated by the observation that surrender payouts substantially exceed life insurers' financial liabilities in practice. For example, surrender payouts correspond to more than six times the volume of insurers' financial liabilities to credit institutions (EIOPA, 2020). Second, policyholders do not immediately invest surrender payouts in the same assets that insurers sold (which would alleviate insurers' price impact). Instead, policyholders might, in the short run, hold more cash or consume part of the surrender value. Indeed, we estimate that a 1% increase in surrender payouts is associated with a 0.65% increase in private consumption (see Appendix D).

3.2 Baseline Results

We simulate 80,000 paths of the financial market 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. To assess the risk posed by surrender options in an environment with rising interest rates, among all simulated paths, we focus on the 5% with the largest annual increase in the 10-year German government bond rate (i.e., the average

[31] We numerically solve Equation (11), choosing the solution with minimal fire sale costs.

increase between $t = 0$ and $t = 10$). Figure 4 (b) illustrates these paths with an interest rate rise. On average, interest rates increase annually by 25 bps. 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. We describe the results focusing on the median outcome across the "interest rate rise" paths. In addition, we report the 25th and 75th percentiles, which illustrate the variation in outcomes implied by the estimated standard deviation of interest rates and surrender decisions.

3.2.1 Slow Pass-Through of Interest Rate Changes. Figure 5 (a) depicts the dynamics of market interest rates, the insurer's investment return and contract returns. The investment return is based on book values, which is the relevant metric to determine contract returns (see Equation 4). The simulated 10-year German government bond rate gradually increases by approximately 25 bps per year. However, the insurer's investment return decreases over time. The reason for this divergence is the long duration of the insurer's investments, which implies that the historical decline in interest rates dominates the investment return dynamics. Old long-term bonds with high yields are gradually replaced by new bonds with relatively lower (yet increasing) yields. Given the initial asset duration of 9.3 years, it takes approximately the same time until the insurer's investment return begins to rise. Thus, there is a slow pass-through of changes in interest rates to the insurer's investment return.

Figure 5 (a) also shows that contract returns closely follow the insurer's investment return and, therefore, the slow pass-through to the investment return translates into a slow pass-through to contract returns. The co-movement of investment and contract returns is intuitive since, during an interest rate rise, existing contracts have relatively low guaranteed returns (implied by initially low interest rates), which, thus, are often not binding. Since contract returns are based on the investment return *after* depreciations (see Equation 4), these may even drive contract returns below the raw investment return (computed before depreciations), as in years $t = 9$ and $t = 10$ in Figure 5 (a).

Since guaranteed returns for new contracts follow a moving average of lagged interest rates, they are mostly driven by historically declining interest rates, similarly to the investment return. As a consequence, the median guaranteed return does not increase above its initial level during the 10 year horizon of the simulations.

Due to these return dynamics, the difference between contract returns and the market interest rate shrinks. As a result, policyholders' incentives to surrender strengthen, as Equation 7 implies. In the simulations, the average surrender rate increases from approximately 3.3% at model start to nearly 12% after 10 years of rising interest rates (see Figure 5 b).[32] A surrender rate of 12% corresponds to the 97th percentile of German life insurers' surrender rates from 1996 to 2019. It is substantially below a surrender rate of 20-25%, which according to Biagini et al. (2021) would constitute a "mass cancellation scenario", and below 40%, which is assumed to reflect a mass cancellation scenario in European insurance regulation. Figure 5 (b) shows that surrender rates increase for the average cohort with wide variation across cohorts. Younger cohorts with a long remaining time to maturity are more sensitive to an increase in interest rates than older cohorts and, thus, drive the increase in surrender rates (in Appendix E we show the surrender rate dynamics for each cohort).

3.2.2 Interest Rate Convexity. The increase in surrender rates reduces the interest rate duration of individual insurance contracts when interest rates rise. Thus, surrender options lead to life insurance convexity. This effect on the contract portfolio's duration is amplified by cross-sectional heterogeneity in surrender rates: younger cohorts are more interest rate sensitive, and thus, their particularly high surrender rates reduce their weight within the insurer's contract portfolio. As a consequence, older cohorts with a shorter duration gain higher weight and further reduce the *average* duration in the contract portfolio. In addition to this downward pressure on the contract portfolio duration, differences in cohort size and

[32] Note that the correlation between surrender rates and interest rates is higher in the simulations than in the empirical analysis in Section 2 since the model starts at a particularly low level of interest rates, which implies that low contract returns amplify the sensitivity of surrender rates (see Equation 7). Indeed, in additional regressions with the data from Section 2, we find that *Interest rates*$^2_{t-1}$ enters with a significantly negative coefficient.

guaranteed returns affect duration dynamics. Older cohorts have higher guaranteed returns, and thus, their cash value grows faster than that of younger cohorts, amplifying the decline in contract portfolio duration. These effects interact with size differences across cohorts and can mitigate or further boost the decline in duration.

To disentangle baseline effects in portfolio composition from the impact of interest-rate-sensitive surrender options, we compare our results to a counterfactual calibration in which the surrender rate is held constant at the initial surrender rate level for each policyholder. We interpret this counterfactual calibration as an environment in which policyholders surrender exclusively due to idiosyncratic liquidity needs. In this case, the duration of contracts is decreasing (see Figure 6 a), consistent with the portfolio composition effect described above: the distribution of contracts shifts from younger contracts with longer duration to older contracts with relatively shorter duration. The average modified duration of the contract portfolio declines from 14.1 years at $t = 0$ to 8.7 years at $t = 10$.

In our baseline calibration, the interest rate sensitivity of surrender rates amplifies the decline in contract duration. In this case, the modified duration declines to 6.5 years at $t = 10$. The difference from the counterfactual calibration with a constant surrender rate combines two effects: (1) reallocation of cash flows *within* contracts, as higher surrender rates reduce contracts' expected lifetime, and (2) changing portfolio composition, as younger contracts are relatively more interest rate sensitive and, thus, have higher surrender rates, which increase the portfolio weight of older contracts with a shorter duration. As a result, the overall duration of the contract portfolio declines by an additional 2 years (or, equivalently, 25%) and even strongly below the duration of the insurer's investments. Hence, a gradual but long-lasting interest rate rise can reverse life insurers' duration gap: although the duration gap is initially negative, i.e., the contract duration is longer than the asset duration, the duration gap becomes positive after 6 years. At this point, the value of insurers' equity capital switches from being long to being short in interest rates.

3.2.3 Free Cash Flow and Asset Sales. High surrender rates translate into large surrender payouts to policyholders. These payouts negatively affect the insurer's free cash flow, as Figure 6 (b) shows. In the counterfactual calibration with constant surrender rates, the free cash flow remains positive. In this case, the total inflows related to the insurer's investment income and premiums exceed the total payouts for matured and surrendered contracts. Instead, in the baseline calibration, large surrender rates drive the free cash flow into negative territory starting after year $t = 7$. The longer the interest rate rise lasts, the larger is the total annual net outflow, which reaches nearly 1.5% of total assets after 10 years of rising interest rates.

As a result, the insurer is forced to sell assets. We compute the volume of asset sales as the sum of net sales within asset classes, $\text{Sales}_t = \sum_{k \in \mathcal{K}} \max\{-(w_t^k A_{t+} - a_{t-}^k), 0\}$. Market segmentation implies that purchases in one asset class cannot offset the price impact of sales in another asset class. Therefore, Sales_t may exceed the insurer's net outflow. In the simulation, the volume of asset sales corresponds to up to 3% of total assets after 10 years of rising interest rates (see Figure 7). Thus, due to portfolio rebalancing in line with the insurer's investment strategy, the volume of actual asset sales exceeds the net cash outflow by approximately 1.5% of total assets.[33]

To assess the price impact of asset sales, we compute the volume-weighted average price impact, $\sum_{k \in \mathcal{K}} \text{Price impact}_t^k \cdot \text{Sales}_t^k / \sum_{k \in \mathcal{K}} \text{Sales}_t^k$ (following the definitions in Equation 10), reflecting the average price impact per EUR 1 sold. In the simulations, the insurer's asset sales depress prices by up to 71 bps. The magnitude of this price impact is economically significant. For example, Massa and Zhang (2021) document that nonfinancial firms reacted to corporate bond price declines of approximately 50 bps by adjusting their debt structure after hurricane Katrina forced insurance companies to sell bonds. Importantly, the annual volume of asset sales and, thus, the price impact increase with the duration of the interest rate

[33]Note that the level of Sales_t depends on the level of market segmentation. The more segmented the market, the larger is the sum of segment-level net sales. By assuming segmentation of the bond market into only two segments, our results are conservative relative to the actual segmentation of markets in practice (e.g., Kubitza (2021) provides empirical evidence for more granular segmentation at the bond issuer level).

rise. The reasons are that an enduring interest rate rise (1) prevents the insurer's investment return from catching up with interest rates and, thereby, bolsters surrender incentives (see Figure 5) and (2) depresses the prices of long-term relative to short-term bonds, which induces insurers to rebalance their investment portfolio (see below).

To what extent are asset sales driven by surrender options? To answer this question, we compare asset sales and the price impact in the baseline calibration to those in a counterfactual calibration with a constant surrender rate. In this counterfactual calibration, sales are driven exclusively by portfolio rebalancing since the free cash flow remains positive, i.e., surrenders do not force the insurer to sell assets (see Figure 6). The difference between this counterfactual calibration and the baseline results reflects the additional impact of dynamic surrenders. The implied *surrender-driven* asset sales amount to nearly 2% of the insurer's assets and depress prices by 37 bps at $t = 10$. Thus, surrender options drive more than half (60%) of asset sales and (52%) of the price impact.

Whereas the price impact is economically significant, we find the resulting costs for the insurer to be small relative to its equity capital. The costs are below 0.2% of the insurer's equity capital (see Appendix E). The reason is the insurer's relatively large capital buffer, which readily absorbs the fire sale costs. Thus, for the representative insurer in our model, the effect of surrender-driven asset sales on financial market prices is economically more significant than the potential risk to the life insurer's solvency.

3.3 Counterfactual Calibration: Role of Long-Term Investments

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

Consistent with the above rationale, Figure 8 shows that a longer duration of the insurer's investments leads to a lower investment return during an interest rate rise. Specifically, the investment return in an average year is approximately 90 bps (29%) smaller when the investment duration is 3.8 years longer, namely, 11.2 instead of 7.4 years. As a result, surrender incentives strengthen: the surrender rate in an average year is approximately 70 bps (10%) higher in case of a longer duration.

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

3.4 Counterfactual Calibration: Role of Investment Strategies

In the baseline calibration, the insurer keeps investment portfolio weights constant over time. However, when the contract duration declines as a result of rising interest rates (see Figure 6), insurers are likely to reduce their asset duration to facilitate duration matching (Domanski et al., 2015). We implement such a dynamic investment strategy in a counterfactual calibration, assuming that the insurer targets a constant relative duration gap between fixed-income investments and contracts.

Figure 9 (a) depicts the asset sales and price impact if the insurer implements the dynamic investment strategy. We find that the peak price impact, 54 bps, is slightly smaller than that with constant portfolio weights. Moreover, the timing substantially differs. Whereas asset sales increase over time with constant portfolio weights, with a dynamic investment strategy, asset sales realize primarily in the early years of an interest rate rise. After approximately 5 years, asset sales and the price impact stabilize at low levels.

Hence, the dynamic investment strategy prevents the insurer from being *forced* to sell assets in late years by (partly) substituting short-term for long-term bonds in early years. This substitution in early years strengthens the pass-through of interest rates, which reduces surrender rates (see Figure 9 b). Figure 10 illustrates the allocation of asset sales. It compares the asset sales by asset class under a dynamic investment strategy with those under constant portfolio weights. In addition to the difference in timing, there is a substantial difference in the assets being sold. If the insurer follows a dynamic investment strategy, it sells almost exclusively long-term bonds to reduce the asset duration, matching the declining duration of insurance contracts. Instead, if the insurer targets constant portfolio weights, it sells almost exclusively short-term bonds. The reason is that the prices of longer-term bonds decline relative to that of shorter-term bonds when interest rates increase. To counteract this shift in relative prices and to maintain constant portfolio weights, the insurer sells short-term rather than long-term bonds.

3.5 Counterfactual Calibration: Market Value Adjustments

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

We implement an MVA to examine how it affects surrender rates and asset sales. For this purpose, we use the same initial balance sheet calibration as in the baseline analysis but assume that, starting at $t = 0$, all cohorts' surrender values are subject to an MVA. The market-value-adjusted surrender value at year-begin $t, t \geq 1$, is $sv^h_{t-1,MVA} = (1-m^h_{t-1})\cdot\vartheta\cdot v^h_{t-1}$, where m^h_{t-1} is the MVA factor. It is calculated as

$$m^h_{t-1} = 1 - \min\left\{ \left(\frac{1 + \tilde{r}^h_{P,t-1}}{1 + \ell + r_{f,t-1,T^h-(t-1)}} \right)^{T-(t-1)}, \vartheta^{-1} \right\}. \tag{12}$$

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

Figure 11 (a) compares the surrender rate in the counterfactual calibration with MVA to that in the baseline calibration. The MVA clearly reduces the surrender rate starting in year 4, after which it stabilizes close to 7%. In the first three years of the model, the surrender rate increases at a similar pace in both calibrations. During this time, MVA factors are not sufficiently large to offset strengthened surrender incentives since the minimum MVA factor is binding for most contracts due to low interest rates (see Appendix E).

The relatively lower surrender rate translates into a lower volume of asset sales and lower price impact. The peak price impact is roughly 25% lower, namely 53 bps with MVA rather than 71 bps in the baseline calibration (see Figure 11 a). Taking into account that portfolio reallocation results in a peak price impact of 34 bps when surrender rates are constant, the MVA reduces the (remaining) surrender-induced price impact by almost 50%, specifically from 37 bps to 19 bps. These results show that an MVA can significantly reduce the interest rate sensitivity of surrender rates and, thereby, the downward pressure on asset prices resulting from surrender-induced asset sales during an interest rate rise.

4 Empirical Predictions and Policy Implications

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

First, we uncover substantial interest rate convexity in life insurance savings contracts. In our baseline calibration, surrender options depress the duration of life insurance contracts by approximately 2 years during an interest rate rise of 25 bps p.a.. This *convexity* is consistent with empirical evidence on the interest rate sensitivity of life insurers' equity prices. For example, by comparing U.S. life insurance products (that typically include surrender options and financial guarantees) to U.K. life insurance products (that typically do *not* include guarantees), 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 duration of investments than of contracts) to reduce their exposure to an interest rate rise. Thereby, convexity provides a possible explanation for why life insurers in most countries exhibit negative duration gaps (e.g., IMF, 2019).[34]

Second, convexity incentivizes insurers to reduce (increase) the duration of their investments during an interest rate rise (decline) to match changes in contract duration. A collective rebalancing can induce upward pressure on long-term relative to short-term yields, analogous to the effect of prepayment options for fixed-rate mortgages (Hanson, 2014). This prediction is consistent with the results in Domanski et al. (2015), who document that German life insurers increase their investments' duration when interest rates decline and that the resulting demand for long-term bonds further reduces long-term yields. Ozdagli and Wang (2019) provide additional empirical evidence for a negative correlation between the level of interest rates and U.S. life insurers' demand for long-term bonds.

Third, our results suggest that surrender options can force life insurers to liquidate a

[34] Note that negative duration gaps 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.

substantial share of their assets. In our baseline calibration, we estimate an asset price impact of surrender-driven asset sales of up to 40 bps when interest rates rise. Thus, our model predicts a positive correlation between the volume of life insurers' asset sales and the yields on insurers' investments. During an interest rate rise, this correlation further amplifies upward pressure on long-term yields since higher surrender rates then motivate asset sales. This pressure to sell assets may be strengthened by an increase in insurers' liquidity demand stemming from other business activities, e.g., from the obligation to post variation margins for interest rate swaps (De Jong et al., 2019).

Asset sales can amplify market instabilities (Brunnermeier and Pedersen, 2009), which raises the question of how to prevent a collective increase in surrender rates when interest rates rise. The primary reason for interest-rate-sensitive surrender incentives is that neither contract returns nor surrender values react to interest rate changes in the short run. Instead, allowing surrender values to fluctuate with asset prices can reduce the interest rate sensitivity of surrender incentives. MVAs adjust surrender values to changes in interest rates by comparing the current and past levels of interest rates. We implement such an MVA in our model and show that it can substantially reduce surrender-driven asset sales during an interest rate rise. Therefore, MVAs can be a viable policy tool to mitigate collective asset sales by life insurers.[35]

Policymakers have suggested the use of surrender penalties and suspensions for the purpose of managing life insurers' liquidity risk (e.g., ESRB, 2020). In contrast to MVAs, large surrender penalties reduce the *average* level of surrender rates. Thus, they are costly for policyholders even in times when interest rates and the volume of insurers' asset sales are low. While a temporary suspension of surrender payouts can mitigate forced asset sales, it seems difficult to adequately time such suspensions since they are necessarily backward looking.[36] Moreover, surrender suspensions can pose significant costs for policyholders with

[35]MVAs are commonly found in U.S. deferred annuities, but not in most European life insurance markets. This observation suggests that it is individually optimal for life insurers not to offer MVAs, e.g., because the liquidity insurance provided by guaranteed surrender values is highly valued by policyholders.

[36]For instance, French regulation allows regulators to temporarily suspend surrender payouts. This leg-

strong liquidity needs. For these reasons, MVAs may be a more effective tool to mitigate surrender-driven asset sales.

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. Thus, life insurance contracts display convexity: their duration declines with a higher level of interest rates.

We empirically document this dynamic in a large panel of German life insurers. 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 in surrender incentives across insurance companies, we argue that this effect is due to policyholders maximizing yield.

A sufficiently strong increase in surrender rates can force life insurers to sell assets, generating downward pressure on asset prices due to insurers' importance as institutional investors. We calibrate a granular model to estimate surrender-driven asset sales and price impact. Simulations predict that an interest rate rise of 25 bps per year boosts surrender rates from 2.5% to nearly 12% after 10 years. These large surrender rates are estimated to force insurers to sell up to 2% of their assets, depressing asset prices by up to 40 bps. The volume of asset sales increases with the duration of insurers' assets, which prevents policyholders from benefiting from rising interest rates and, thereby, amplifies surrender rates. If insurers follow a dynamic investment strategy, matching the duration of investments and insurance contracts, they predominantly sell long-term rather than short-term assets. These asset sales occur swiftly after interest rates begin to rise and subside after roughly 5 years. Instead, if insurers target constant portfolio weights, mostly short-term assets are sold, and the volume

islation is specifically designed to strengthen financial stability if collective surrenders during an interest rate rise lead to fragility in the life insurance sector (see https://www.ca-assurances.com/en/Channels/Trade-and-regulation/The-Sapin-2-Law-what-it-will-change-in-the-insurance-sector).

of asset sales increases over time. These results highlight insurers' investment strategy as an important determinant of the level, timing, and allocation of surrender-driven asset sales.

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

References

Albizzati, M. O. and Geman, H. (1994). Interest Rate Risk Management and Valuation of the Surrender Option in Life Insurance Policies. *Journal of Risk and Insurance*, 61(4):616–637.

Allen, F. and Carletti, E. (2006). Credit Risk Transfer and Contagion. *Journal of Monetary Economics*, 53(1):89–111.

Andonov, A. and Rauh, J. D. (2021). The Return Expectations of Public Pension Funds. *Review of Financial Studies*, forthcoming.

Artavanis, N., Paravisini, D., Robles-Garcia, C., Seru, A., and Tsoutsoura, M. (2019). Deposit Withdrawals. Working paper.

Assekurata (2016). Assekurata Life Insurance Market Outlook 2016/2017. Technical report.

BaFin (2019). German Federal Financial Supervisory Authority (BaFin) Statistics on Primary Insurers (Erstversicherungsstatistik).

Bauer, D., Gao, J., Moenig, T., Ulm, E. R., and Zhu, N. (2017). Policyholder Exercise Behavior in Life Insurance: The State of Affairs. *North American Actuarial Journal*, 21(4):485–501.

Becker, B. and Ivashina, V. (2015). Reaching for Yield in the Bond Market. *Journal of Finance*, 70(5):1863–1902.

Becker, B., Opp, M. M., and Saidi, F. (2021). Regulatory Forbearance in the U.S. Insurance Industry: The Effects of Removing Capital Requirements for an Asset Class. *Review of Financial Studies*, forthcoming.

Biagini, F., Huber, T., Jaspersen, J. G., and Mazzon, A. (2021). Estimating Extreme Cancellation Rates in Life Insurance. *Journal of Risk & Insurance*, forthcoming.

Brennan, M., Rodney, C., and Vine, M. (2013). What May Cause Insurance Companies to Fail - and How This Influences Our Criteria. Standard and Poor's RatingsDirect.

Bretscher, L., Schmid, L., Sen, I., and Sharma, V. Institutional Corporate Bond Demand. Working Paper.

Brewer, Elijah, M. T. H. and Strahan, P. E. (1993). Why the Life Insurance Industry Did Not Face an "S&L-type" Crisis. *Economic Perspectives. Federal Reserve Bank of Chicago*, 17(5):12–24.

Brown, J. R. (2001). Private Pensions, Mortality Risk, and the Decision to Annuitize. *Journal of Public Economics*, 82(1):29–62.

Brunnermeier, M. and Pedersen, L. H. (2009). Market Liquidity and Funding Liquidity. *Review of Financial Studies*, 22(6):2201–2238.

Cancryn, Adam (2015). Life Insurers Get Lift from Fed's Rate Hike, but New Challenges Lie Ahead. Standard & Poor's Global Market Intelligence - Insurance Insight.

Chang, H. and Schmeiser, H. (2021). Surrender and Liquidity Risk in Life Insurance. *Quantitative Finance*, forthcoming.

Chodorow-Reich, G., Ghent, A., and Haddad, V. (2020). Asset Insulators. *Review of Financial Studies*, 34(3):1509–1539.

Coval, J. and Stafford, E. (2007). Asset Fire Sales (and Purchase) in Equity Markets. *Journal of Financial Economics*, 86(2):479–512.

Dar, A. and Dodds, C. (1989). Interest Rates, the Emergency Fund Hypothesis and Saving through Endowment Policies: Some Empirical Evidence for the UK. *Journal of Risk and Insurance*, 56(3):415–433.

De Jong, A., Draghiciu, A., Fache Rousová, L., Fontana, A., and Letizia, E. (2019). Impact of Margining Practices on Insurers' Liquidity: An Analysis of Interest Rate Swaps Positions. In *EIOPA Financial Stability Report 2019* (pp. 90-104).

DeAngelo, H., DeAngelo, L., and Gilson, S. C. (1994). The Collapse of First Executive Corporation: Junk Bonds, Adverse Publicity, and the 'Run on the Bank' Phenomenon. *Journal of Financial Economics*, 36(3):287–336.

Deutsche Bundesbank (2018). Financial Stability Review 2018. Available at www.bundesbank.de.

Diamond, D. W. and Dybvig, P. H. (1982). Bank Runs, Deposit Insurance, and Liquidity. *Journal of Political Economy*, 91(3):401–419.

Domanski, D., Shin, H. S., and Sushko, V. (2015). The Hunt for Duration: Not Waving but Drowning? *BIS Working Paper*, 519.

Drehmann, M. and Nikolaou, K. (2010). Funding Liquidity Risk: Definition and Measurement. *BIS Working Paper*, 316.

ECB (2017). Financial Stability Review 2017. *European Central Bank*.

EIOPA (2014). Insurance Stress Test 2014. *European Insurance and Occupational Pensions Authority*.

EIOPA (2016). Insurance Stress Test 2016. *European Insurance and Occupational Pensions Authority*.

EIOPA (2017a). Investment Behaviour Report. *European Insurance and Occupational Pensions Authority*.

EIOPA (2017b). Systemic Risk and Macroprudential Policy in Insurance. *European Insurance and Occupational Pensions Authority*.

EIOPA (2018). Insurance Stress Test 2018 - Technical Specifications. *European Insurance and Occupational Pensions Authority*.

EIOPA (2019). Report on Insurers' Asset and Liability Management in Relation to the Illiquidity of Their Liabilities. *European Insurance and Occupational Pensions Authority*.

EIOPA (2020). Insurance Statistics. Available at http://eiopa.europa.eu/. *European Insurance and Occupational Pensions Authority.*

EIOPA (2021). Methodological Principles of Insurance Stress Testing - Liquidity Component. *European Insurance and Occupational Pensions Authority*.

Eling, M. and Holder, S. (2013). Maximum Technical Interest Rates in Life Insurance in Europe and the United States: An Overview and Comparison. *Geneva Papers on Risk and Insurance - Issues and Practice*, 38(2):354–375.

Eling, M. and Kiesenbauer, D. (2014). What Policy Features Determine Life Insurance Lapses? An Analysis of the German Market. *Journal of Risk and Insurance*, 81(2):241–269.

Ellul, A., Jotikasthira, C., Kartasheva, A., Lundblad, C. T., and Wagner, W. (2021). Insurers as Asset Managers and Systemic Risk. Working Paper.

Ellul, A., Jotikasthira, C., and Lundblad, C. T. (2011). Regulatory Pressure and Fire Sales in the Corporate Bond Market. *Journal of Financial Economics*, 101:596–620.

Ellul, A., Jotikasthira, C., Lundblad, C. T., and Wang, Y. (2015). Is Historical Cost Accounting a Panacea? Market Stress, Incentive Distortions, and Gains Trading. *Journal of Finance*, 70(6):2489–2538.

ESRB (2015). Report on Systemic Risks in the EU Insurance Sector. *European Systemic Risk Board*.

ESRB (2020). Enhancing the Macroprudential Dimension of Solvency II. *European Systemic Risk Board*.

Fabozzi, F. J. (2000). *Cash Management - Products & Strategies: Products and Strategies*. John Wiley & Sons.

Förstemann, T. (2019). How a Positive Interest Rate Shock Might Stress Life Insurers. Working Paper.

GDV (2016). Statistical Yearbook of German Insurance 2016. *German Insurance Association*.

Geneva Association (2012). Surrenders in the Life Insurance Industry and Their Impact on Liquidity. Technical report.

Girardi, G., Hanley, K. W., Nikolova, S., Pelizzon, L., and Getmansky Sherman, M. (2021). Portfolio Similarity and Asset Liquidation in the Insurance Industry. *Journal of Financial Economics*, 142(1):69–96.

Gottlieb, D. and Smetters, K. (2021). Lapse-Based Insurance. *American Economic Review*, 11(8):2377–2416.

Greenwood, R., Hanson, S., and Stein, J. (2010). A Gap-Filling Theory of Corporate Debt Maturity Choice. *Journal of Finance*, 65(3):993–1028.

Greenwood, R., Landier, A., and Thesmar, D. (2015). Vulnerable Banks. *Journal of Financial Economics*, 115(3):471–485.

Greenwood, R. and Vayanos, D. (2010). Price Pressure in the Government Bond Market. *American Economic Review: Papers & Proceedings*, 100(2):585–590.

Greenwood, R. and Vissing-Jorgensen, A. (2018). The Impact of Pensions and Insurance on Global Yield Curves. Working Paper.

Grosen, A. and Jorgensen, P. L. (2002). Life Insurance Liabilities at Market Value: An Analysis of Insolvency Risk, Bonus Policy, and Regulatory Intervention Rules in a Barrier Option Framework. *Journal of Risk and Insurance*, 69(1):63–91.

Hanson, S. G. (2014). Mortgage Convexity. *Journal of Financial Economics*, 113(2):270–299.

Hartley, D., Paulson, A. L., and Rosen, R. J. (2017). Measuring Interest Rate Risk in the Life Insurance Sector: The U.S. and the U.K. In Hufeld, F., Koijen, R. S. J., and Thimann, C., editors, *The Economics, Regulation, and Systemic Risk of Insurance Markets*. Oxford University Press.

Hombert, J. and Lyonnet, V. (2021). Can Risk Be Shared across Investor Cohorts? Evidence from a Popular Savings Product. Working Paper.

Hombert, J., Möhlmann, A., and Weiß, M. (2021). Inter-Cohort Risk Sharing with Long-Term Guarantees: Evidence from German Participating Contracts. *Deutsche Bundesbank Discussion Paper*, 10/2021.

IMF (2016). Global Financial Stability Report - Potent Policies for a Successful Normalization. World Economic and Financial Surveys. *International Monetary Fund*.

IMF (2017). Global Financial Stability Report - Is Growth at Risk? World Economic and Financial Surveys. *International Monetary Fund*.

IMF (2019). Global Financial Stability Report - Lower for Longer. World Economic and Financial Surveys. *International Monetary Fund*.

IMF (2021). Global Financial Stability Report - COVID-19, Crypto, and Climate: Navigating Challenging Transitions. World Economic and Financial Surveys. *International Monetary Fund*.

Jackson, H. E. and Symons, E. L. J. (1999). *Regulation of Financial Institutions*. American Casebook Series. West Group.

Jansen, K. (2021). Long-Term Investors, Demand Shifts, and Yields. Working Paper.

Kiesenbauer, D. (2012). Main Determinants of Lapse in the German Life Insurance Industry. *North American Actuarial Journal*, 16(1):52–73.

Koijen, R. S. J. and Yogo, M. (2016). Shadow Insurance. *Econometrica*, 84(3):1265–1287.

Koijen, R. S. J. and Yogo, M. (2019). A Demand System Approach to Asset Pricing. *Journal of Political Economy*, 127(4):1475–1515.

Koijen, R. S. J. and Yogo, M. (2021). The Fragility of Market Risk Insurance. *Journal of Finance*, forthcoming.

Koijen, R. S. J. and Yogo, M. (2022). Understanding the Ownership Structure of Corporate Bonds. *NBER Working Paper*, 29679.

Kubitza, C. (2021). Investor-Driven Corporate Finance: Evidence from Insurance Markets. Working Paper.

Kuo, W., Tasi, C., and Chen, W. K. (2003). An Empirical Study on the Lapse Rate: The Cointegration Approach. *Journal of Risk and Insurance*, 70(3):489–508.

Laeven, L. and Valencia, F. (2018). Systemic Banking Crises Database: An Update. *IMF Working Paper*, 18/206.

Liu, Y., Rossi, S., and Yun, H. (2021). Insurance Companies and the Propagation of Liquidity Shocks to the Real Economy. Working Paper.

Lusardi, A. and Mitchell, O. S. (2014). The Economic Importance of Financial Literacy: Theory and Evidence. *Journal of Economic Literature*, 52(1):5–44.

Massa, M. and Zhang, L. (2021). The Spillover Effects of Hurricane Katrina on Corporate Bonds and the Choice between Bank and Bond Financing. *Journal of Financial and Quantitative Analysis*, 56(3):885–913.

Mitchell, O. S. and Moore, J. F. (1998). Can Americans Afford to Retire? New Evidence on Retirement Saving Adequacy. *Journal of Risk and Insurance*, 65(3):371–400.

Moody's Investors Service (2021). Life Insurers US: A Little Inflation Is Credit Positive; A Sizable Spike Would Hurt.

NAIC (2020a). Statistical Compilation of Annual Statement Information for Life/Health Insurance Companies in 2019. *National Association of Insurance Commissioners*.

NAIC (2020b). U.S. Insurance Industry Cash and Invested Assets at Year-End 2019. Capital Markets Special Report. *National Association of Insurance Commissioners*.

NAIC (2021). NAIC 2020 Liquidity Stress Test Framework. *National Association of Insurance Commissioners*.

Nolte, S. and Schneider, J. C. (2017). Don't Lapse into Temptation: A Behavioral Explanation for Policy Surrender. *Journal of Banking and Finance*, 79:12–27.

Ozdagli, A. and Wang, Z. K. (2019). Interest Rates and Insurance Company Investment Behavior. Working Paper.

Russell, D. T., Fier, S. G., Carson, J. M., and Dumm, R. E. (2013). An Empirical Analysis of Life Insurance Policy Surrender Activity. *Journal of Insurance Issues*, 36(1):35–57.

Sen, I. (2020). Regulatory Limits to Risk Management. Working Paper.

Swiss Re Institute (2019). World Insurance: The Great Pivot East Continues. Sigma 3/2019.

Timmer, Y. (2018). Cyclical Investment Behavior across Financial Institutions. *Journal of Financial Economics*, 129(2):268–286.

Vasicek, O. (1977). An Equilibrium Characterization of the Term Structure. *Journal of Financial Economics*, 5(2):177–188.

Vayanos, D. and Vila, J.-L. (2021). A Preferred-Habitat Model of the Term Structure of Interest Rates. *Econometrica*, 89(1):77–112.

Figures and Tables

Figure 1. Economic Significance of Surrender Payouts in Europe.
The figure depicts the cross-country distribution of the ratio of life insurance surrender payouts to (a) payouts to life insurance policyholders and (b) life insurance premiums net of reinsurance ceded (all at the country level), weighted by total life insurance reserves. The sample includes Austria, Belgium, Bulgaria, Croatia, Cyprus, the Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Liechtenstein, Lithuania, Luxembourg, Malta, the Netherlands, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, and the U.K. *Source:* EIOPA (2020).

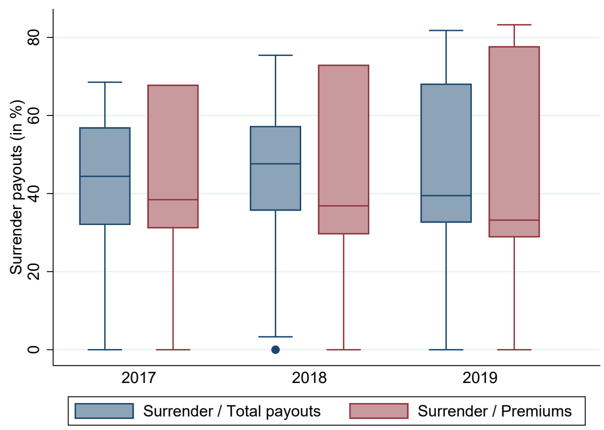
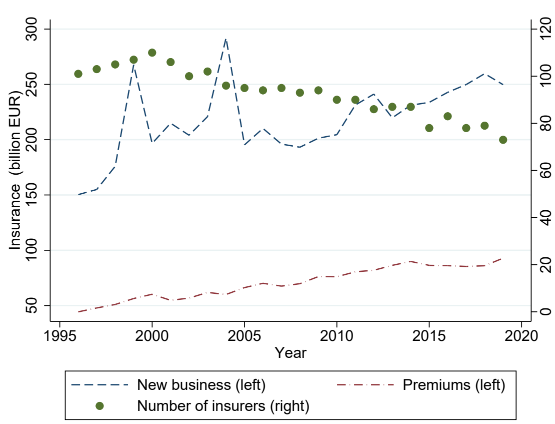
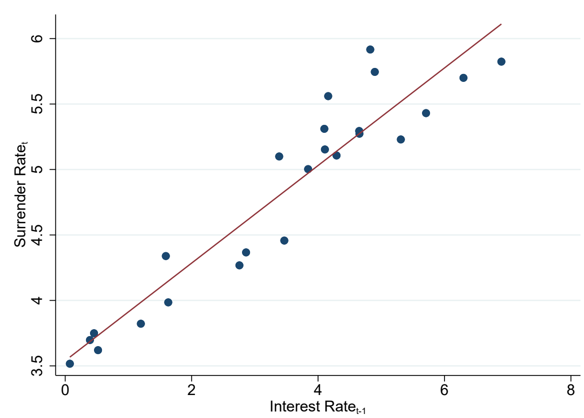


Figure 2. Sample Characteristics and Visual Inspection of Surrender and Interest Rates.
Figure (a) depicts total annual insurance premiums and the volume of new business in billion EUR (left axis) and the number of insurers in each year (right axis) in the sample. New business is measured by volume insured and, thus, exceeds premiums paid. Figure (b) represents a binscatter plot of surrender rates and the 10-year German government bond rate. For each realization of the 10-year German government bond rate, the conditional mean of insurer-level surrender rates is plotted as a scatter point. The figure also includes the line of best fit from a univariate OLS regression.



(a) Sample Size and Dynamics.



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

Figure 3. Surrender Rate Calibration.
The figure depicts the surrender rate for a 40-year savings contract as a function of the contract return $\tilde{r}_P$ and for different times to contract maturity, TtM, of 30 and 40 years. In the figure, we assume a flat risk-free rate of $r_f = 1.22\%$, corresponding to the 10-year German government bond yield in 2015, and a surrender penalty equal to $1 - \vartheta = 2.5\%$.

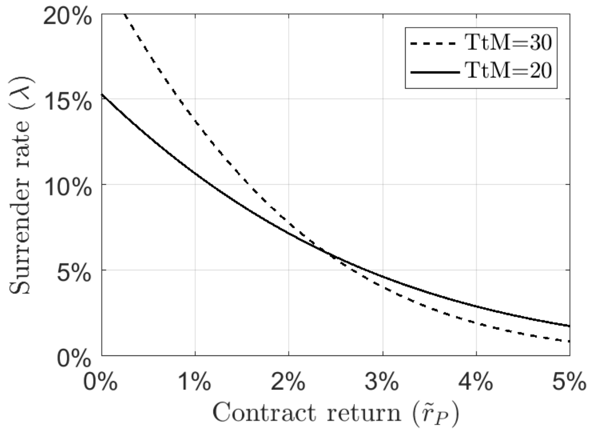
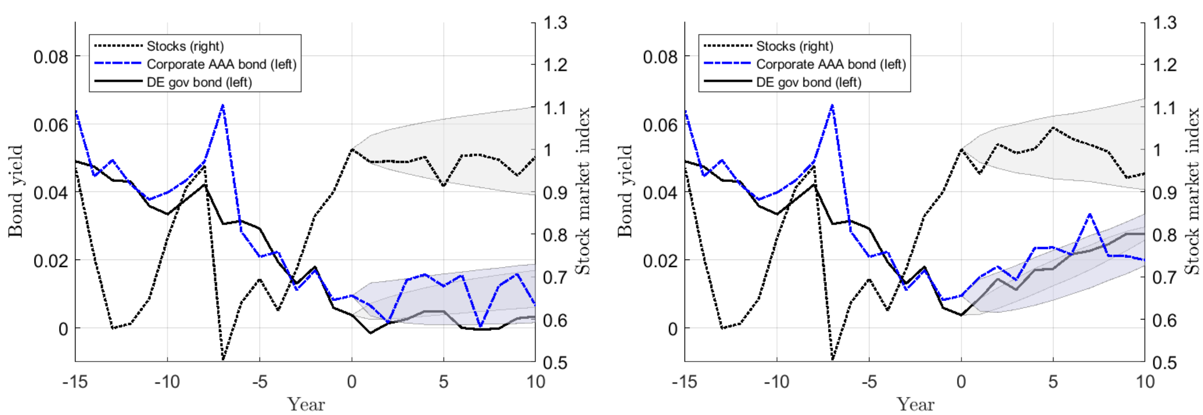


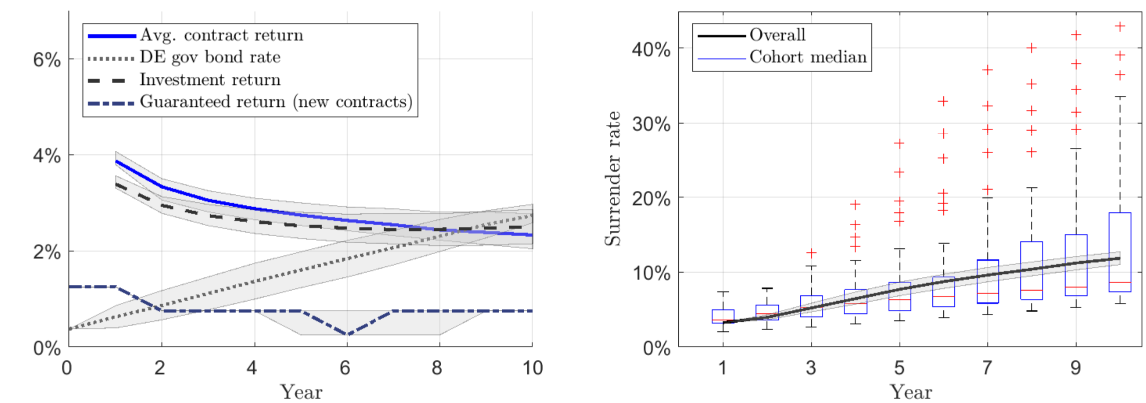
Figure 4. Financial Market Dynamics: Historical and Simulated.
The figures depicts one exemplary simulated path and the 25th / 75th percentiles of simulated 10-year German government bond rates, AAA corporate bond rates, and the European stock market index from year 0 on. Prior to year 0, we show the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



(1) All Paths.

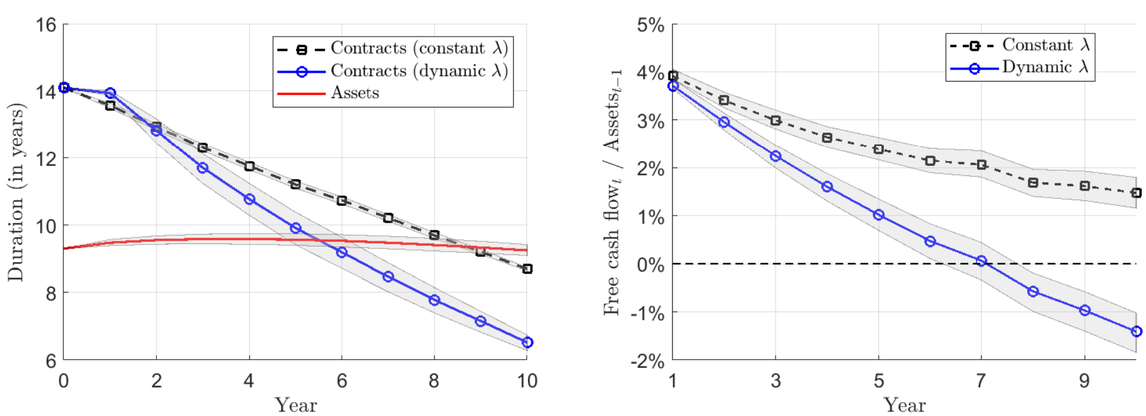
(2) Paths with Rising Interest Rates.

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). The investment return is computed as the ratio of investment income (as in Equation 4) without considering depreciations relative to the insurer's lagged book value of assets. Figure (b) depicts the share of surrendered contracts (straight lines; median and 25th / 75th percentiles) and the distribution of each cohort's median surrender rate across cohorts (boxes; defined by the 25th, 50th, and 75th percentiles).



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

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



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

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 1 sold, defined as the average asset class-specific price impact (see Equation 10) weighted by the asset class-specific volume of sales. The figure shows the median and 25th/75th percentile for each year.

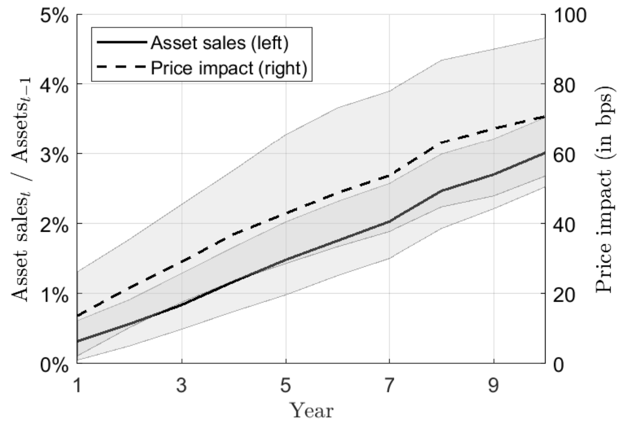


Figure 8. Counterfactual Calibration: Role of Long-Term Investments.
The figure depicts the insurer's investment return (left axis), ratio of asset sales to lagged total assets (left axis), and surrender rate (right axis), all for an average year and with the median and the 25th/75th percentiles across simulations. We vary the initial duration of the insurer's government bond portfolio (holding the ratio of durations across different types of government bonds constant), and denote the resulting initial duration of fixed-income investments on the x-axis.

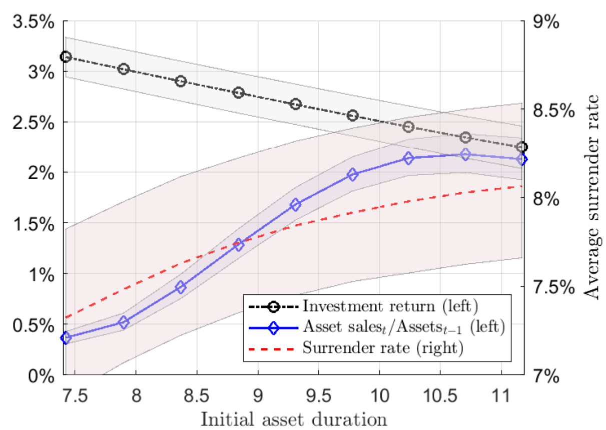
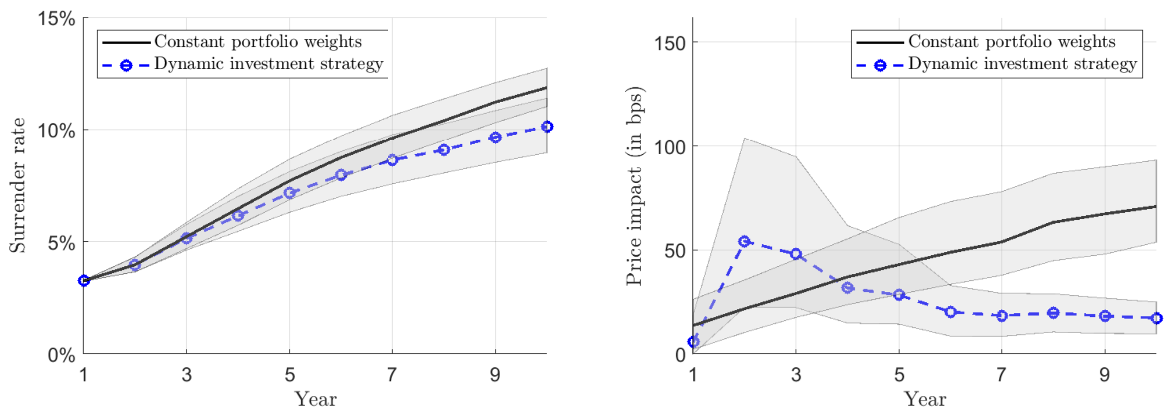


Figure 9. Counterfactual Calibration: Surrender Rate and Price Impact with Dynamic Investment Strategy.

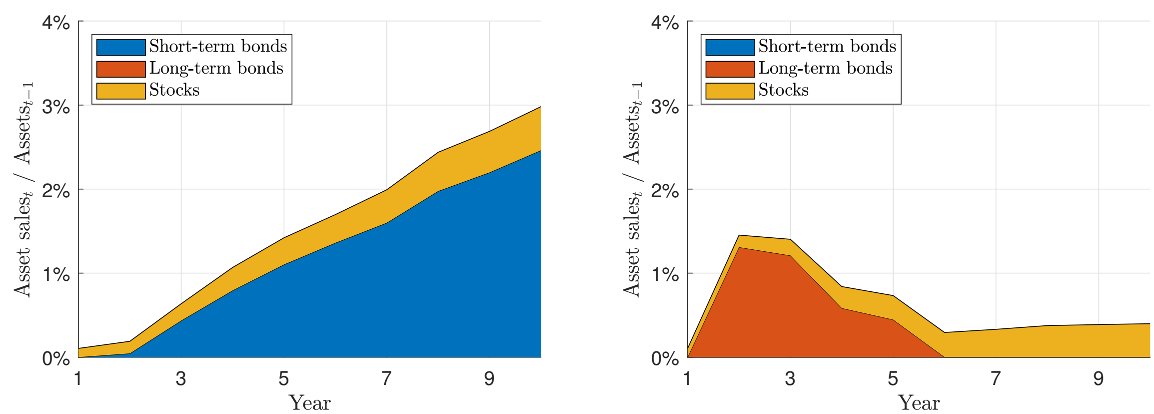
Figure (a) compares the insurer's surrender rate in the baseline calibration with constant portfolio weights to that in a counterfactual calibration with a dynamic investment strategy. Figure (b) compares the insurer's price impact in the baseline calibration with constant portfolio weights to that in a counterfactual calibration with a dynamic investment strategy. Both figures show the median and 25th/75th percentile for each year.



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

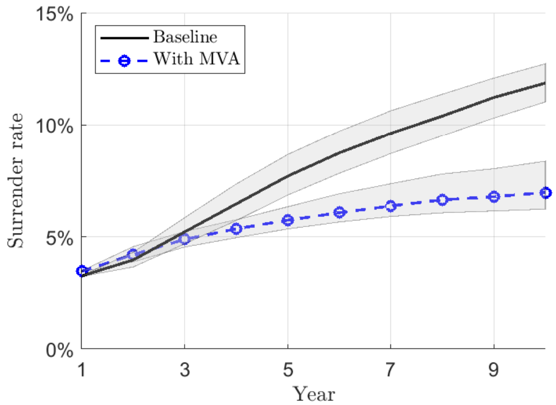
Figure 10. Counterfactual Calibration: Asset Sales across Asset Classes.

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

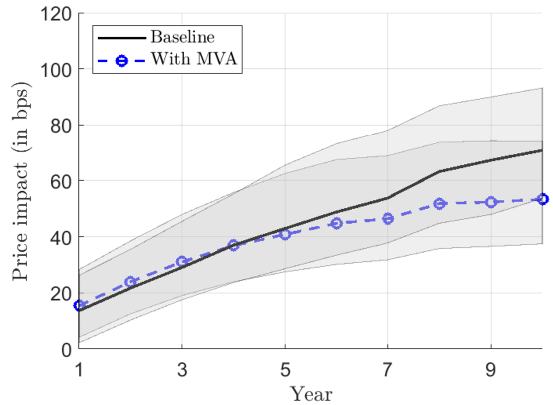


(a) Constant Portfolio Weights. (b) Dynamic Investment Strategy.

Figure 11. Counterfactual Calibration: Market Value Adjustment.
Figure (a) compares the insurer's surrender rate in a counterfactual calibration with market value adjustments (MVAs) to that in the baseline calibration. Figure (b) compares the insurer's price impact in a counterfactual calibration with MVAs to that in the baseline calibration. Both figures show the median and 25th/75th percentile for each year.



(a) Surrender Rate.



(b) Price Impact.

Table 1. Summary Statistics.
Surrender rate, age, new business, and investment return are at the insurer-year level retrieved from BaFin's *Erstversicherungsstatistik*. The remaining variables are at the year level, retrieved from German Bundesbank (interest rate), BIS (inflation), OECD (GDP and investment growth), Laeven and Valencia (2018) (crisis indicator), and the German association of insurers 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$_{t-1}$ (aggregate)	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 the 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	Young contracts	Full		Young contracts	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	3.26%
Average guaranteed return	3.12%
Avg. remaining contract lifetime	25.60
Equity capital / assets	9.00%
Modified Duration (Contracts)	14.10
Modified Duration (Assets)	9.31

Internet Appendix for

"Life Insurance Convexity"

Christian Kubitza[*], Nicolaus Grochola[†], Helmut Gründl[‡]

[*]Corresponding author, University of Bonn, Institute of Finance and Statistics, Germany. christian.kubitza@uni-bonn.de.

[†]Goethe University Frankfurt, International Center for Insurance Regulation, Germany. grochola@finance.uni-frankfurt.de.

[‡]Goethe University Frankfurt, International Center for Insurance Regulation, Germany. gruendl@finance.uni-frankfurt.de.

A Surrender Options in the U.S.

In the U.S., surrender options differ across life insurance contract types. Life insurance products with cash value also entail surrender options. These products include universal life and whole life insurance as well as variable and deferred annuities (Berends et al., 2013).

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

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

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 100 bps annually. However, 10% of the cash value can typically be withdrawn without a penalty in the first contract years.

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

B Empirical Analysis: Additional Details and Results

B.1 Additional Details

When constructing the data sample based on BaFin's Erstversichererstatistik, we use the following rules:

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

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

   where insurance in $\text{force}_{i,t-1}$ 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.
4. To construct the annual German government bond rate, we retrieve end-of-month yields from the German Bundesbank and take annual averages.

B.2 Additional Results

Table IA.1. Surrender Rates and Interest Rates: Robustness.
Columns (1) to (3) present estimates from specifications of the form

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

Column (1) presents an IV estimate, where the main explanatory variable, the 10-year German government bond rate, Interest rate$_{t-1}$, is instrumented by the 10-year U.S. treasury rate. Columns (2) and (3) present a reduced-form estimate, where the main explanatory variable is the federal funds rate, FFR$_{t-1}$. Columns (4) and (5) regress annual changes in surrender rates on annual changes in interest rates, both from $t-1$ to t, in the following specification:

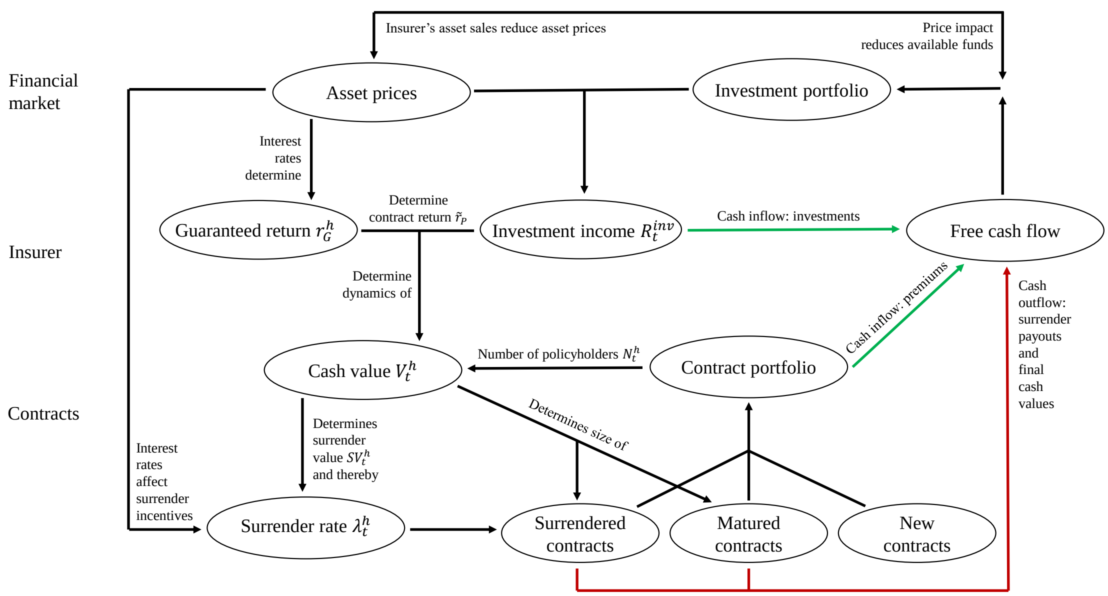
$$\Delta\text{Surrender rate}_{i,t} = \alpha \cdot \Delta\text{Interest rate}_{t} + \beta \cdot X_{i,t-1} + \gamma \cdot Y_{t-1} + u_i + \varepsilon_{i,t}.$$

$1\{\Delta\text{Interest Rate}_t > 0\}$ is an indicator for an increase in the German government bond rate from $t-1$ to t. The sample is at the insurer-by-year level and covers the years 1996 to 2019. $X_{i,t-1}$ is a vector of insurer-level controls, which includes the 1-year lagged investment return and the 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)	(5)
Dependent variable:	Surrender rate			ΔSurrender rate	
	IV	OLS			
Interest rate$_{t-1}$	0.162***		0.176***		
	[3.26]		[2.83]		
Federal funds rate$_{t-1}$		0.054**	-0.001		
		[2.54]	[-0.04]		
ΔInterest rate$_t$				0.185***	0.154*
				[4.08]	[1.87]
$1\{\Delta\text{Interest rate}_t > 0\}$					-0.139
					[-1.21]
$1\{\Delta\text{Interest rate}_t > 0\} \times \Delta\text{Interest rate}_t$					0.541**
					[2.23]
Macro controls	Y	Y	Y	Y	Y
Insurer controls	Y	Y	Y	Y	Y
Insurer FE	Y	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	2,046	2,046
No. of insurers	159	159	159	150	150

C Model and Calibration Details

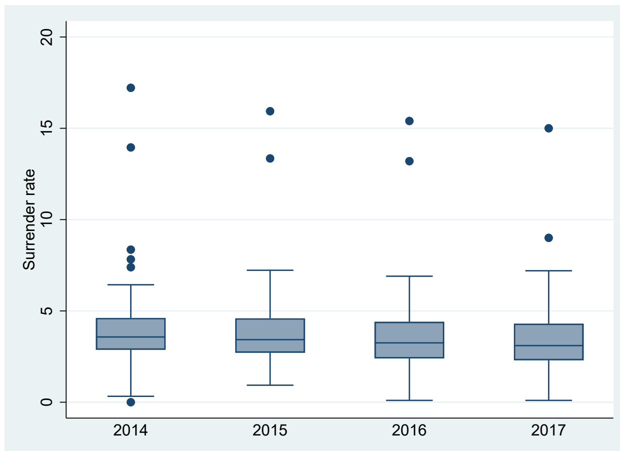
Figure IA.1. Illustration of Model Ingredients and Dynamics.
The financial market model determines asset prices and, in particular, government bond rates, which determine the guaranteed return for the new cohort of contracts in year h, r_G^h. Jointly with the insurer's investment portfolio, asset prices also determine the insurer's investment income R_t^{inv}. A fraction ξ of the investment income is passed on to policyholders. The maximum of the guaranteed return and the policyholder's fraction of the investment income determines the contract return $\tilde{r}_P$, which drives the dynamics of life insurance contracts' cash value V_t^h. The cash value determines the surrender value SV_t^h. Surrender decisions are based on comparing SV_t^h with current interest rates, resulting in the surrender rate λ_t^h. Cash values also determine the size of surrendered and matured contracts. Contract portfolio dynamics are jointly determined by the volume of surrendered, matured, and new contracts and, thereby, reflected in the number of policyholders N_t^h of cohort h. The insurer's total free cash flow is given by the sum of investment income and premiums net of cash outflows due to surrendered and matured contracts. Excess cash is reinvested, whereas a negative free cash flow forces the insurer to sell assets. Asset sales reduce asset prices and, thereby, negatively impact the funds available for reinvestment.



C.1 Calibration of Surrender Decisions

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

Figure IA.2. Distribution of Surrender Rates across German Life Insurers.



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

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

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

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

(3) To calibrate the sensitivity to 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 across insurers by contract portfolio size) among those insurers with the 10% smallest difference between investment return and 30-year government bond rate, which is 24.6%,

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

This step relies on the assumption that an insurer's observed investment return is a reasonable proxy for its contracts' returns.[2]

The resulting calibration is $(\beta_0, \beta_1, \beta_2) = (0.4933, 1.1129, 0.2390)$.

C.2 Accounting for Insurance Liabilities

Under European statutory accounting following the Solvency II regulation, insurance liabilities reflect the present value of contract payouts. We compute the present value of liabilities in cohort h at time t as follows:

$$PV_t^h = V_t^h \left(\sum_{j=1}^{T^h - t} \frac{\vartheta \lambda_t^h (1-\lambda_t^h)^{j-1} \prod_{h=1}^{j-1} \hat{r}_{P,t+h}^h}{(1 - r_{f,t,j-1})^{j-1}} + \frac{(1-\lambda_t^h)^{T^h - t} \prod_{h=1}^{T^h - t} \hat{r}_{P,t+h}^h}{(1 + r_{f,t,T^h - t})^{T^h - t}} \right). \tag{IA.3}$$

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

[2] 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 3.16% (according to Assekurata, 2016), while the guaranteed return for new contracts was 1.25%.

C.3 Calibration of the Initial Contract Portfolio

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

- the volume of life insurance savings contracts ("Kapitalversicherungen") newly issued in year h, N^h, obtained from the German insurance association, GDV (in million EUR)[3],
- the life insurance sector's surrender rate, $\tilde{\lambda}_t$,
  - 1996–2015: for the median German life insurer (weighted across insurers by contract portfolio size) according to BaFin's Erstversichererstatistik
  - 1976–1995: the average surrender rate reported by the German insurance association, GDV, scaled by the ratio of the BaFin surrender rate to the GDV surrender rate from 1996 to account for differences in the underlying set of life insurers
- the realized contract return of German life insurance contracts
  - 1996–2015: reported by Assekurata, a rating agency for German life insurers[4]
  - 1976–1995: predicted by fitting a linear model to the average contract return reported by Assekurata for 1996–2015 using the 10-year moving average of 5-year German government bond rates reported in the IMF's International Financial Statistics as explanatory variable (the R^2 is 91%). We use bond rates from the IMF's statistics because of their long available history.

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

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

2015. Instead, contract dynamics might have deviated in practice due to the presence of one-time premiums, heterogeneity in the surrender rate and contract return, and time-varying insurance supply.

To evaluate the representativeness of the initial contract portfolio, we use two key portfolio characteristics: the average guaranteed return per contract and the portfolio's modified duration.[5] Assekurata (2016) reports an average guaranteed return of 2.97% for German life insurers in 2015. The German association of insurers reports a modified duration of 14.1 years for the median German life insurer. Following the assumptions above, our initial portfolio would exhibit a much shorter duration. In this case, the portfolio weight of older contracts (with a short remaining time to maturity and, thus, short duration) is too large. To offset this bias, we modify the size of cohorts $h \in \{-39, ..., 0\}$ as follows:

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

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

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

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

where

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

is the present value of contract cash flows at year-end t and $\hat{r}_{P,t+h}^h$ is the predicted contract return for year $t + h$ as described in Section C.2.

C.4 Calibration of the Insurer's Investment Portfolio

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

The weights within subportfolios are based on Berdin et al. (2017) and EIOPA (2014) and reported in Table IA.2. We include a large home bias toward German government bonds, which, however, has little impact on our results. Due to the absence of more granular data, we calibrate real estate and stock weights to yield a plausible home bias of 60% for German real estate and stocks and equally distribute the remaining weights.

Table IA.2. Investment Portfolio Allocation.
The table depicts the weights and average modified duration of each asset class in the insurer's investment portfolio. The calibration is based on EIOPA (2014, 2016) and GDV (2016).

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

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

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

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

C.5 Calibration of the Short-Rate Model

Short rate dynamics are given by

$$dr_t = \alpha_r(\theta_r - r_t)dt + \sigma_r dW_t^r, \tag{IA.4}$$

where r_t is the short rate at time t, W_t^r is a standard Brownian motion, $\alpha_r > 0$ is the speed of mean reversion, $\sigma_r > 0$ is the volatility, and θ_r is the level of mean reversion. Under the assumption of arbitrage-free interest rates, Equation (IA.4) specifies the term structure of annually compounded interest rates at time t for maturities τ, $\{r_{f,t,\tau}\}_{\tau \geq 0}$. Following Brigo and Mercurio (2006), the price of a zero-coupon bond at time t with maturity at $t + \tau \geq t$ is

$$(1 + r_{f,t,\tau})^{-\tau} = A(\tau) e \left[-B(\tau) r_t \right], \tag{IA.5}$$

where

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

and

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

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

We calibrate the short rate volatility σ_r using a maximum-likelihood estimator based on the monthly Euro OverNight Index Average (EONIA) from December 2000 to November 2015.[6] 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

C.6 Calibration of the Financial Market Model

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

$$ds_t^j = k^j (\bar{s}^j - s_t^j) dt + \sigma^j dW_t^j. \tag{IA.6}$$

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

[6]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*.

We calibrate bond spreads and stock and real estate returns based on monthly data from December 2000 to November 2015. Corporate bond rates are given by the effective yield of the AAA/AA/A/BBB-subset of the ICE BofAML US Corporate Master Index (obtained from *FRED St. Louis*), which tracks the performance of U.S. dollar-denominated investment-grade rated corporate debt publicly issued in the U.S. domestic market. To account for the different inflation (expectations) between the EU and U.S., we calculate bond spreads with respect to the yield of U.S. treasuries with a maturity of 10 years (obtained from *FRED St. Louis*).[7] 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.3 describes the sample of bond spreads. Note that we retrieve bond rates (and spreads) for maturities of 1 to 20 years for each government bond, while corporate bond spreads are calculated by comparing the effective yield of the ICE BofAML US Corporate Index to the 10-year yield. Since we assume the same spread for each maturity, we calibrate the spread process $\{s_t^j\}_t$ for the average spread across maturities in the case of government bonds. Parameter estimates are based on maximum likelihood and reported in Table IA.3. We assume that coupons are equal to the (government or corporate) bond yield at issuance. Given coupons, we price bonds using the term structure of risk-free rates $r_{f,\tau,t}$ and spreads s_t^j.

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.4 reports the descriptive statistics for monthly log-returns. We calibrate the GBM drift and volatility with maximum-likelihood estimates for monthly log-returns, which are also reported in Table IA.4. 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.

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

Table IA.3. Summary Statistics and Calibration of Bond Spreads.
The table reports summary statistics and maximum-likelihood estimates for the long-term mean ($\bar{s}$), speed of mean reversion (k), and volatility (σ) of the Ornstein-Uhlenbeck process $s^j(t) = k^j(\bar{s}^j - s^j(t))dt + \sigma^j dW^j(t)$ for monthly bond spreads between (a) government bond rates and German government bonds and (b) corporate bond rates and the 10Y U.S. treasury bond rate from December 2000 to November 2015. Government bond rates include observations for 1-year to 20-year maturities, and the calibration is based on the average spread across maturities. Corporate bond spreads are based on the effective yield of ICE BofAML US Corporate Indices and 10-year U.S. treasury rates. *Source: Authors' calculations, Thomson Reuters Eikon (government bonds), FRED St. Louis (corporate bonds).*

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

Table IA.4. Summary Statistics and Calibration for Stocks and Real Estate.
The table reports summary statistics and maximum-likelihood estimates for geometric Brownian motions for monthly stock and real estate returns from December 2000 to November 2015. Stock returns are based on the STOXX Europe 600 index, and real estate returns are based on the MSCI Europe real estate index. *Source: Authors' calculations, Thomson Reuters Eikon.*

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

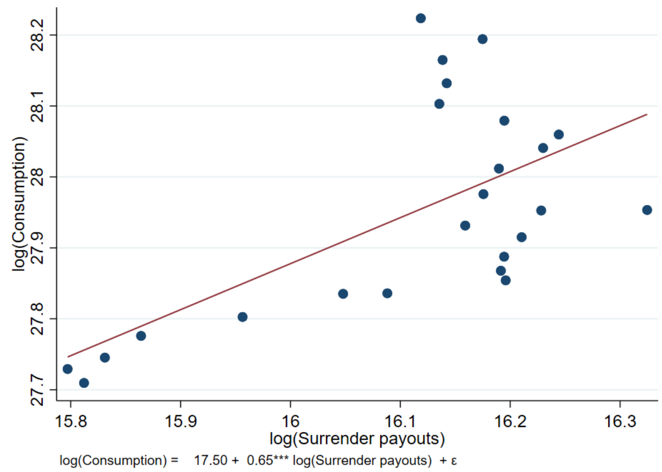
Finally, we correlate all stochastic processes via a Cholesky decomposition of their diffusion terms. Table IA.5 reports the correlation coefficients based on monthly residuals after fitting bond spreads, stock and real estate returns.

Table IA.5. Correlation Matrix for Financial Market Processes.
The table reports the correlation coefficients for monthly residuals from December 2000 to November 2015 of the short rate (EONIA), government bond spreads for France (FR), the Netherlands (NL), Italy (IT), and Spain (ES), corporate bond spreads for AAA-, AA-, A-, and BBB-rated bonds, stocks, and real estate returns, after fitting to the short rate and spreads to Ornstein-Uhlenbeck processes and stocks and real estate returns to geometric Brownian motions.

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

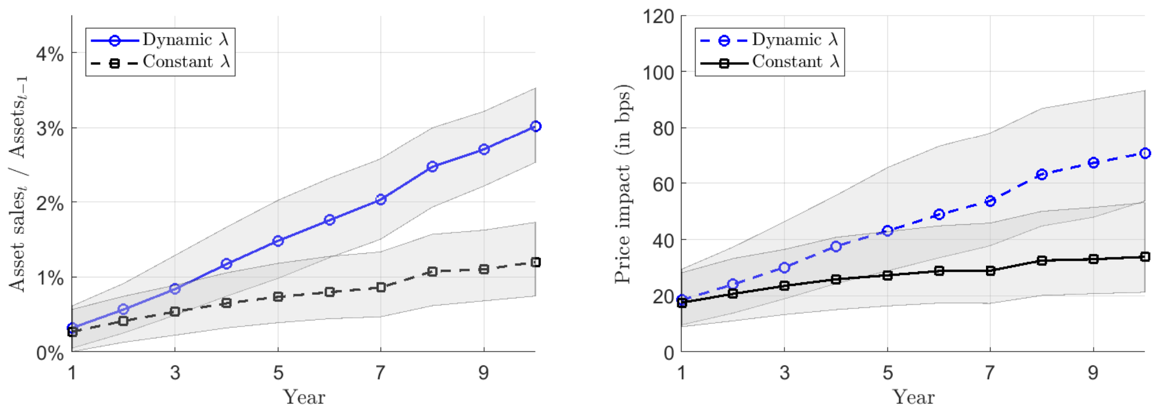
D Surrender Payouts and Consumption

Figure IA.3. Correlation Between Surrender Payouts and Private Consumption.
The figure plots the logarithm of annual aggregate surrender payouts (x-axis) and the logarithm of total private consumption expenditures (y-axis) in Germany from 1996 to 2019 as scatter points. A univariate regression implies that consumption expenditures increase by 0.65% when surrender payouts rise by 1%. *Sources: BaFin (surrender payouts), OECD (private consumption expenditures).*



E Additional Simulation Results

Figure IA.4. Asset Sales and Price Impact: Constant vs. Dynamic Surrender Rate.
Figure (a) depicts the insurer's asset sales relative to the previous year's total assets in the case of a constant surrender rate and in the case in which surrender rates respond to the market environment. Figure (b) depicts the average price impact in the case of a constant surrender rate and in the case in which surrender rates respond to the market environment. The figure shows the median and 25th/75th percentile for each year.



(a) Asset sales.

(b) Price impact

Figure IA.5. Fire Sale Costs and Price Impact.
The figure depicts the fire sale cost of asset sales relative to the previous year's total equity capital (left axis) and the price impact (right axis) as defined in Equation (10) for the baseline calibration. The figure shows the median and 25th/75th percentile for each year.

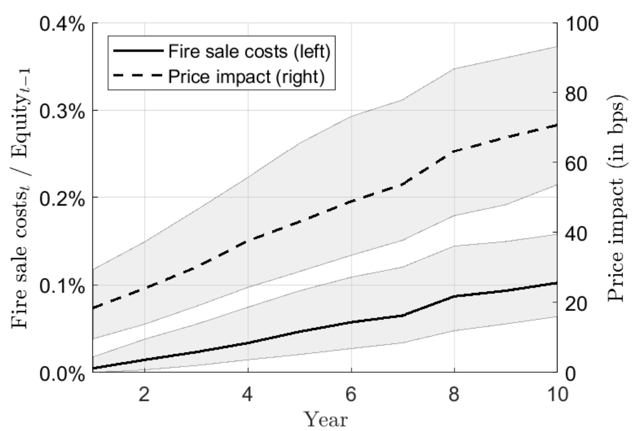
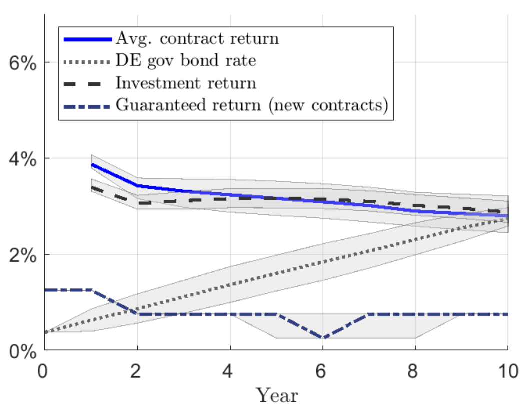
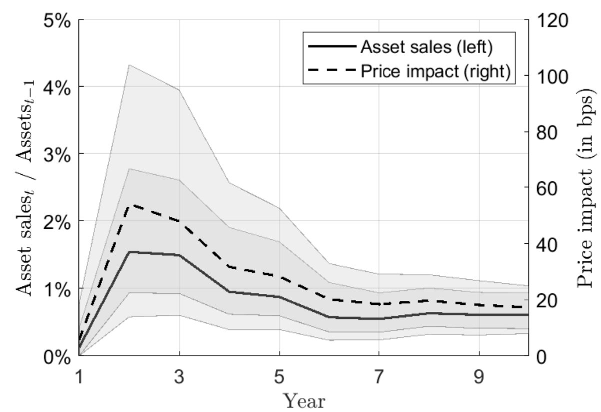


Figure IA.6. Counterfactual Calibration: Returns, Asset Sales, Price Impact with Dynamic Investment Strategy.

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



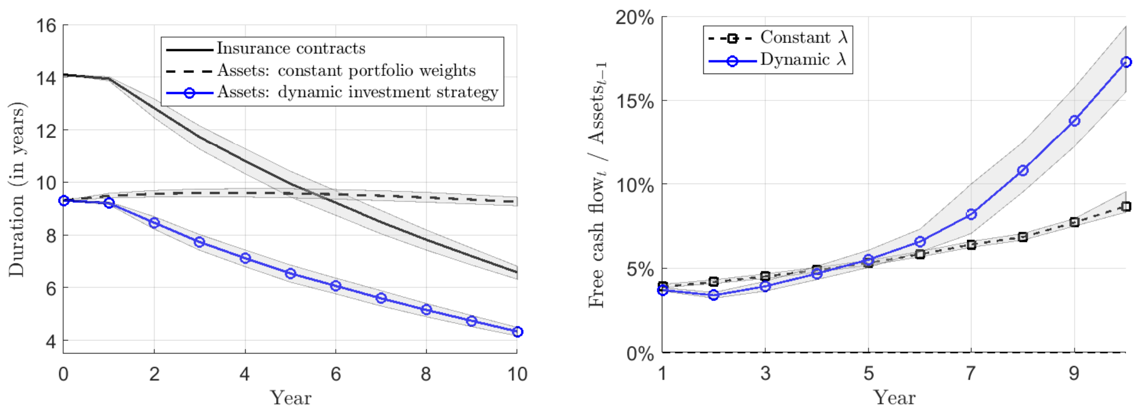
(a) Interest rate and returns.



(b) Asset sales and price impact.

Figure IA.7. 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.

Figure IA.8. Counterfactual Calibration: Market Value Adjustment Factor.

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

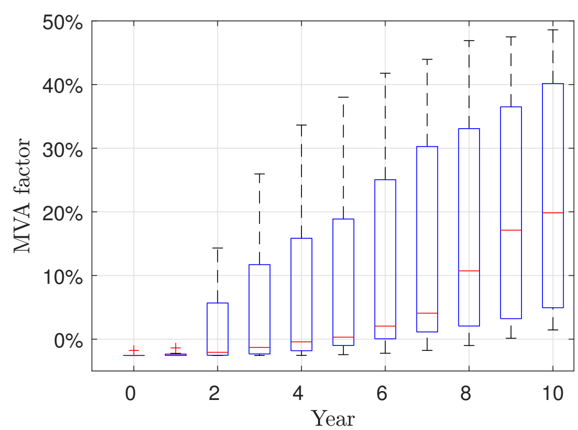
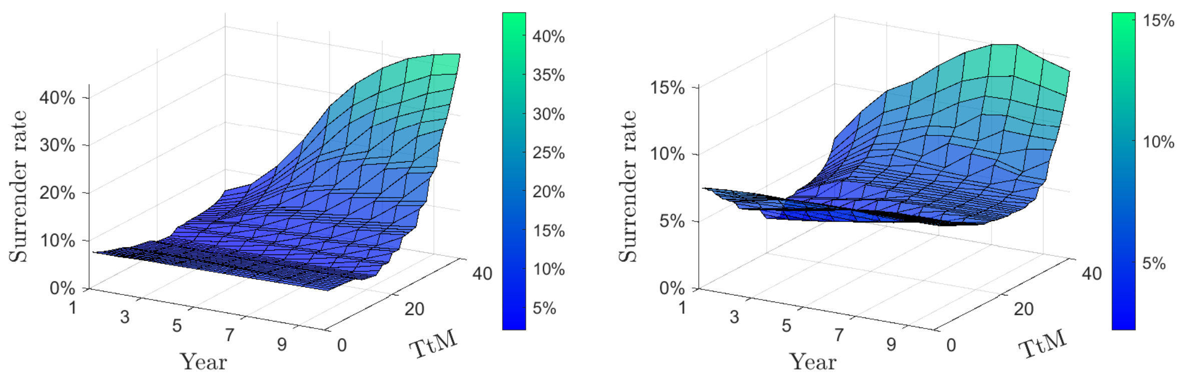


Figure IA.9. Surrender Rate Across Cohorts.

The figures depict each cohort's median surrender rate across time. Cohorts are characterized by contracts' remaining time to maturity ("TtM"). Figure (a) is based on the baseline results. Figure (b) is based on a counterfactual calibration that includes a market value adjustment.



(a) Baseline. (b) With MVA.

References

Assekurata (2016). Assekurata Life Insurance Market Outlook 2016/2017. Technical report.

Berdin, E., Pancaro, C., and Kok, C. (2017). A Stochastic Forward-Looking Model to Assess the Profitability and Solvency of European Insurers. *ECB Working Paper*, 2028.

Berends, K., McMenamin, R., Plestis, T., and Rosen, R. J. (2013). The Sensitivity of Life Insurance Firms to Interest Rate Changes. *Federal Reserve Bank of Chicago - Economic Perspectives*, 37(2):47–78.

Brigo, D. and Mercurio, F. (2006). *Interest Rate Models: Theory and Practice*. Berlin, Heidelberg, Paris: Springer.

EIOPA (2014). Insurance Stress Test 2014. *European Insurance and Occupational Pensions Authority*.

EIOPA (2016). Insurance Stress Test 2016. *European Insurance and Occupational Pensions Authority*.

GDV (2016). Statistical Yearbook of German Insurance 2016. *German Insurance Association*.

Laeven, L. and Valencia, F. (2018). Systemic Banking Crises Database: An Update. *IMF Working Paper*, 18/206.

NAIC (2017). Standard Nonforfeiture Law for Individual Deferred Annuities. *National Association of Insurance Commissioners*.

NAIC (2021). Annuity Disclosure Model Regulation. *National Association of Insurance Commissioners*.