# Life insurance convexity[*]

PRELIMINARY DRAFT

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# Life insurance convexity


## Abstract

Life insurers massively sell savings policies that guarantee minimum withdrawals. When market interest rates increase, these guarantees become in-the-money, incentivizing withdrawals. We empirically document this effect by exploiting partly hand-collected insurer-level data. A one-standard-deviation increase in interest rates leads to an increase in withdrawal rates by 0.3 standard deviations. Thus, an interest rate rise can force insurers to sell assets. We build a granular model to estimate resulting fire sale externalities. Forced sales reduce asset prices by up to 1% and insurers' equity capital by up to 15bps. They are primarily driven by insurers' long-dated investments.



**Keywords:** Life insurance; Liquidity risk; Interest rates; Fire sales; Systemic risk

**JEL Classification:** G22; E52; G32; G28

*"[...] 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 important financial intermediaries that absorb household risk and facilitate retirement saving. For example, roughly 40% of U.S. and European households' net worth is invested in life insurance and pension funds.[2] As a result, life insurers are large in size and important institutional investors on financial markets. They hold a vast amount of financial assets, namely 20.4 trn USD worldwide, which corresponds to 10% of global financial assets (IMF (2016)).

A distinguishing feature of life insurance policies are surrender options. These options provide policyholders with the opportunity to withdraw an *ex-ante guaranteed* surrender (cash) value, in a similar fashion as withdrawal options for bank deposits. Most life insurance policies in practice include such surrender options – typically without a penalty (see EIOPA (2019)). In this paper, we argue that the guarantees embedded in surrender options expose life insurers to aggregate interest rate risk and can force them to simultaneously sell assets. Specifically, we provide empirical evidence that an increase in interest rates leads to more policy surrender activity, and then estimate the magnitude of forced asset sales and the resulting market price impact in a calibrated model.

Since surrender values are ex ante guaranteed, they are insensitive toward changes in asset prices. Thus, the option to surrender becomes relatively more valuable when asset prices fall relative to an insurance policy's expected payout at maturity. This is the case when market interest rates rise: higher interest rates reduce the value of insurers' legacy (long-term) assets, which prevents insurers from passing changes in market rates fully through to policy returns. Instead, policy returns react slowly to changes in interest rate. Hence, when interest rates rise, the present value of holding policies until maturity declines while the surrender value is fixed. Therefore, the incentive to surrender becomes stronger.

Consistent with this mechanism, the first main contribution of this paper is to provide causal

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

[2] U.S. life insurance policy cash values were roughly 47% of the median U.S. household's net worth (excluding investment in own home) in 2014 (*Source: U.S. census Wealth and Asset Ownership for Households: 2014*). In the EU, investment in life insurance and pension funds was 39% of total households' assets in an average year from 2016 to 2018 (ECB (2019)).

empirical evidence that a rise in market interest rates leads to more life insurance surrender activity. For this purpose, we exploit partly hand-collected panel data for the annual share of surrendered policies (the *surrender rate*) for each German life insurer since 1996. Controlling for time-invariant heterogeneity across insurers and for macroeconomic characteristics, we show that a one-standard deviation increase in German government bond rates (by 1.9ppt) relates to an increase in the surrender rate by 0.3 standard deviations (by 0.8ppt). A back-of-the-envelope calculation shows that this effect roughly corresponds to an increase in payouts by 4 bn EUR. It is thus economically significant. The magnitude of the effect significantly declines with the level and volume of ex-ante guaranteed minimum policy returns and, thus, the interest-rate sensitivity - of policies, controlling for aggregate trends by including year fixed effects.

To further push causal identification, we exploit changes in U.S. monetary policy as an instrument for German government bond rates. Since German life insurers' investment in U.S. bonds is negligible, the instrument addresses the concern that asset sales caused by higher surrender rates bias the baseline estimate. The instrumental variable estimates are significant and close in magnitude compared to the baseline model. These findings confirm the robustness of the effect and are consistent with an asset sale channel of surrender activity.

The empirical analysis implies that life insurance policies' duration decreases with higher interest rates. Thus, the relation between the present value of life insurance and interest rates is *convex*.[3] Life insurance convexity due to surrender options is reversed to mortgage convexity due to prepayment activity: higher interest rates lead to more life insurance surrender but *less* mortgage prepayment activity (e.g., Hanson (2014)).

We document that surrender payments are economically significant, even when interest rates are low. European life insurers paid 364 bn EUR for surrendered policies in 2018, roughly 43% of their net premium income (EIOPA (2020)).[4] Hence, the liquidity risk implied by surrender options is not negligible. A rise in surrender activity drains insurers' cash flow, and might - simultaneously - force them to liquidate assets. Recent studies document a significant price impact of institutional

[3]We call an asset (positively) convex (in interest rates) if its modified duration $D(r) = -P'(r)/P$ is decreasing with yields, i.e., if $D'(r) < 0$, where $P$ is price and $r$ is yield. This definition is motivated by the fact that $D'(r)$ determines whether matching of asset and liability durations hedges insurers against interest rate risk, as we discuss in Section 4. The definition is slightly narrower than the definition used by Hanson (2014), who defines convexity by $D'(r) < D(r)^2$.

[4]Similarly, U.S. life insurers paid out 350 bn USD, corresponding to 58% of their net premium income (NAIC (2019)).

investors – and especially insurers' – investment behavior (e.g., Ellul et al. (2011), Greenwood and Vissing-Jorgensen (2018), Koijen and Yogo (2019), Girardi et al. (2018)). Therefore, collective asset sales forced by surrenders may exert downward pressure on asset prices, a fear stressed by policymakers (e.g., ESRB (2015b, 2020) and EIOPA (2017b, 2019)). As a result, there is strong emphasis on life insurers' liquidity risk in recent regulatory efforts (e.g., by IAIS (2018), ESRB (2020), and the NAIC Liquidity Assessment (EX) Subgroup). To guide policy, it is important to estimate the economic significance of costs and potential externalities that arise from surrender options and forced asset sales.

This serves as motivation for the second main contribution of this paper, which is to document and quantify the risk of forced asset sales resulting from surrender options - from an individual insurer's as well as from a financial stability perspective. For this purpose, we develop and calibrate a detailed dynamic model for the cash flows and balance sheet of life insurers. We empirically calibrate the model to an average German life insurer. Building on a stochastic financial market model, we simulate an interest rate rise by roughly 20bps per year, which is consistent with the historical evolution of German government bond rates. The interest rate rise incentivizes more policyholders to surrender. We estimate that the increased surrender activity forces life insurers' to sell roughly 1.5% of their assets annually. These forced asset sales depress asset prices by up to 1% and eat up insurers' equity capital by up to 15bps annually. We show that the increase in surrender activity and, thus, forced asset sales are driven by insurers' long investment horizon. The longer the asset investments' duration, the slower life insurance policy returns adapt to increasing market interest rates and, thus, the stronger are surrender incentives.

These results show that surrender options are an important, but previously overlooked characteristic of life insurance policies. They provide a rationale for policymakers' effort to regulate surrender activity, which we discuss in detail. The model also provides an estimate for the convexity of life insurance policies. It predicts that surrender options reduce life insurance policies' modified duration by roughly 4 to 5 years when interest rates rise.

The convexity of life insurance is important since it provides an explanation for why life insurers maintain large negative duration gaps in practice (i.e., longer-dated liabilities than assets; see, e.g., IMF (2017, p. 16)).[5] Life insurance convexity reduces the sensitivity of life insurance liabilities'

[5] Koijen and Yogo (2020) discuss other potential explanations for why life insurers maintain negative duration

present value toward interest rate changes. Thus, a duration gap, i.e., a longer duration of liabilities than assets, effectively hedges life insurers against interest rate risk. Moreover, our model also highlights that negative duration gaps alleviate fire sale externalities arising from surrender options since policy returns adapt faster to market interest rates if assets have a shorter duration. Therefore, regulatory efforts that push life insurers to reduce duration gaps can have the adverse side effect of increasing fire sale externalities during an interest rate rise.

Regulators and previous studies emphasize that policy surrenders might result in run-like situations that collectively drain life insurers' liquidity and solvency, potentially causing fire sale spillovers to financial markets (e.g., Acharya et al. (2009); Russell et al. (2013); ESRB (2015b, 2020); ECB (2017); Deutsche Bundesbank (2018); Förstemann (2019)). Despite this awareness of the risks resulting from surrender options, their effect on insurers' liquidity and potential fire sale externalities is still ambiguous. Our study contributes to the literature by filling this gap.

First, we complement studies on the fragility of non-bank institutions to liquidity risk. Traditionally, the literature has focused on bank runs that are motivated by the fear that a bank might not be able to pay out all its depositors (e.g., Diamond and Dybvig (1982)). Recent studies also explore bank deposit withdrawals that are driven by fundamentals (e.g., Artavanis et al. (2019)). Fundamentals-based deposit withdrawals are similar to life insurance surrenders in this paper to the extent that both are driven by yield-maximizing households who compare the present value of withdrawing to that of not-withdrawing. Focusing on insurers, Förstemann (2019) presents a one-period model in which it is optimal for all policyholders to surrender if they doubt a life insurer's ability to serve contractually guaranteed commitments upon an instantaneous interest rate rise. Similarly, Chang and Schmeiser (2020) consider life insurers' bankruptcy risk in an option pricing model with asset illiquidity and optimal surrender exercise. Complementing these studies, we propose an empirically calibrated model of cash flows and surrender incentives that we use to quantify fire sale costs and externalities when surrenders force life insurers to sell assets.

Second, we contribute to a growing literature on the role of insurers to absorb household risk and implications for financial fragility. On the one hand, surrender options protect policyholders against liquidity shocks; on the other hand, we show that surrender options can cause fire sale externalities under plausible assumptions. Hombert and Lyonnet (2019) document that life insurers

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gaps.

facilitate risk sharing across policyholder generations. Chodorow-Reich et al. (2020) argue that insurers' long-term investment horizon and stable funding insulate policyholders from short-term asset price fluctuations. Our model complements this rationale of asset insulation as we show that long-term investments also slow down the pass-through of interest rate changes to policy returns and, thereby, increase incentives for policyholders to surrender policies when interest rates increase – impairing insurer's funding liquidity. Thus, our results point toward a trade-off between the benefit of holding longer term assets for asset insulation and shorter term assets to maintain stable long-term funding. Koijen and Yogo (2015, 2016, 2020) and Sen (2020) highlight fragility in life insurance intermediation that arises from regulatory frictions. In our model, fragility arises due to policy characteristics. Gottlieb and Smetters (2016) propose a competitive market model in which life insurers (ex-post) profit from policy surrenders and thus (ex-ante) encourage policyholders to surrender. Their model provides a rationale for why life insurers provide surrender options, while our results point toward the fire externalities that can arise from collective exercise of the surrender option. Therefore, policies that remove incentives for correlated surrender can be potentially welfare-increasing – e.g., by de-coupling surrender incentives from interest rates using market value adjustments (MVAs) of surrender values (discussed in detail by Förstemann (2019)).

Third, we add to studies that explore the risk of fire sales as a transmission channel for systemic risk. A growing literature empirically documents that the investment behavior of insurers (and, more generally, institutional investors) significantly affects asset prices (e.g., Ellul et al. (2011, 2015), He and Krishnamurthy (2013), Greenwood and Vissing-Jorgensen (2018), Girardi et al. (2018), Chaderina et al. (2018), Koijen and Yogo (2019)). In the empirically calibrated models of Greenwood et al. (2015) and Ellul et al. (2020), systemic risk results from fire sales of banks and insurers that seek to replenish their capital ratio by deleveraging and de-risking after an exogenous income shock, respectively. We add in particular to Ellul et al. (2020)'s model, in which life insurers de-risk by selling illiquid bonds and, thereby, reduce capital requirements. We complement their approach as asset sales are forced by surrendering policyholders in our model. Similar to Greenwood et al. (2015), fire sales reduce insurers' leverage in our model, but with the difference that they are forced by creditors (i.e., policyholders).

Finally, our empirical results support the so-called *interest rate hypothesis*, which states that surrender activity increases with interest rates and relates to a large debate in the insurance literature, dating back at least to Dar and Dodds (1989). A variety of studies examines the relationship between interest and surrender rates (e.g., Kuo et al. (2003), Kiesenbauer (2012), Eling and Kiesenbauer (2014)) and, more generally, explores reasons for life insurance surrender (e.g., Fang and Kung (2012), Gemmo and Götz (2016), Nolte and Schneider (2017)). By inspecting the *mechanism* through which interest rates affect surrender activity, we move this literature an important step forward, toward a causal interpretation. Our results show that policyholders' surrender activity is more sensitive toward interest rate changes when policies are relatively young and have low guaranteed returns. Extending previous studies, our specification alleviates the concern that omitted changes in insurers' business environment cause a positive correlation between interest and surrender rates as we include year fixed effects.

The remainder of this paper proceeds as follows. Section 1 provides an overview of the institutional background. In Section 2 we provide empirical evidence that interest rates increase surrender activity. We quantify the effects of surrender activity on life insurer liquidity and financial market externalities in Section 3, where we present and calibrate a model of life insurance savings policies, cash flows, policyholders' surrender decisions, and the financial market. Section 4 discusses empirical predictions and policy implications and Section 5 concludes.

# 1 Institutional background

## 1.1 Life insurance policies and surrender options

In this paper, we focus on life insurance savings policies. Policyholders pay premiums, typically annually, which are invested by the insurer. Premiums appear as insurance reserves on the liability side of the insurer's balance sheet and are invested in a portfolio of assets. At a policy's maturity date, savings are paid out as a lump sum or converted into an annuity. Policies broadly differ in terms of investment strategies: unit- and index-linked policies (similarly to variable annuities) allow policyholders to determine the investment allocation. Instead, insurers determine the investment strategy for participating (i.e., not unit-linked) policies. Most life insurance policies in the Europe (63% of life insurance reserves in 2019) – and particularly in Germany (88%) – are participating policies (EIOPA (2020)).[6]

88% of European (unit-linked and participating) life insurance policies can be surrendered (as a share of insurance reserves, see EIOPA (2019)). Almost all participating policies with surrender options also include an ex ante guaranteed surrender value, namely 91% (in the sense that the value of underlying assets can fall below the surrender value). Guaranteed surrender values are less common for unit-linked policies (23%), for which policyholders bear most of the investment risk. Since the majority of European life insurance policies is not unit-linked (EIOPA (2020)), the overall share of policies with surrender option and guaranteed surrender value is substantial, namely 66% of all European life insurance policies (EIOPA (2019)). This corresponds to 5.6 trn EUR in life insurance reserves in 2019 (EIOPA (2020)).

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

Within the EU, Germany is among the countries with the highest provision of surrender options and guaranteed surrender values (next to Italy, Austria, Belgium, Portugal, Malta, and France, see EIOPA (2019)), as well as policy return guarantees (ESRB (2015a)). For participating life insurance policies in Germany, the guaranteed surrender value equals the accumulated cash value as of the previous year less an administrative surrender penalty (see German Insurance Contract Act, Section 169). As a consequence, once the cash value is determined, the surrender value is independent of market developments, such as fluctuations in interest rates. Due to the provision of ex ante guaranteed minimum annual policy returns, there is a lower bound for surrender values that is fixed at policy begin. These policy characteristics are similar in other countries, such as the U.S. (see Appendix A). Consequently, when policyholders choose to surrender, they earn the

[6] Throughout the paper, “Europe” refers to the European Economic Area (EEA), which is the geographic area for which the European regulator EIOPA provides standardized statistics (EIOPA (2020)). The EEA includes the members of the European Union (e.g., Germany, France, and Italy) as well as Iceland, Liechtenstein, Norway, and the UK.

difference between the surrender value and the market value of the assets supporting their policies – which is positive if asset prices are low.

### 1.2 Economic significance of surrender payments

We assess the economic significance of surrender activity drawing on data retrieved from EIOPA (2020) and the NAIC (2019) about life insurers' balance sheets as well as premiums, claims and expenses at level. In total, surrender payments in 2018 were 364 bn EUR in Europe, thereof 20 bn EUR in Germany, and 304 bn EUR (equivalently, 350 bn USD) in the U.S. Surrender payments in 2018 correspond to 46.2% of total life insurance claims and benefits of non-surrendered policies in Europe (on aggregate) and 82% in the U.S. Thus, surrender payments comprise a large share of insurer's cash outflows.

In relation to cash inflows, we find that surrender payments account for 43% of net written premiums in the European life insurance market and 58% in the U.S. Also, when we additionally account for other insurer cash flows (namely investment income, insurance benefits, and expenses) surrender payments are economically significant, e.g., 24% of the residual cash flow (12.3 bn EUR) in Germany in 2018 (BaFin (2019)). Therefore, the magnitude of surrender payments is economically highly significant relative to insurers' cash flows.

There is wide country level variation in the relation of surrender rates to insurance premiums across countries, ranging from 2.6% (Norway) to 73.1% (U.K.) as we show in Figure 1. An important determinant for this variation is product type: we find that variation in the share of unit-linked policies (relative to life insurance reserves) explains 17% of the variation in surrender payments relative to premiums across EU countries in 2018 (the correlation is 41%). Thus, although unit-linked policies do often not guarantee surrender values, they relate to relatively large surrender payments in general - highlighting the liquid nature of these policies. Other potential determinants for heterogeneity in surrender rates are the design of surrender options, tax systems, and the macroeconomic environment.

To be able to pay out surrender values, life insurers might need to sell assets. Life insurers traditionally choose long-term asset investments, which are often illiquid (EIOPA (2017a); NAIC (2020); Chodorow-Reich et al. (2020)). In total, 41% of European life insurers' assets in 2018 are

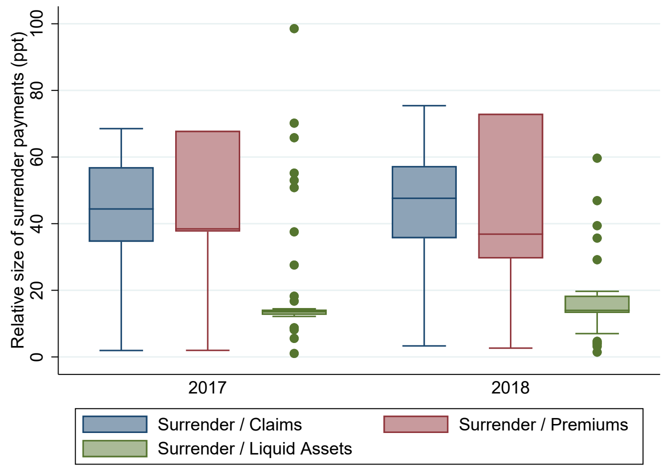



**Figure 1.** Economic significance of surrender payments in Europe.
The figure depicts the ratio of total life insurance surrender payments in European (EEA) countries over (a) technical reserves for life insurance products (including unit- and index linked policies but excluding health), (b) life insurance premiums (net of reinsurance), and (c) liquid assets (defined as the sum of cash and deposits, common equity, equity and money market mutual funds, and central government, treasury, and central bank bonds). The figure covers Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Liechtenstein, Lithuania, Luxembourg, Malta, Netherlands, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, and the U.K., except for Bulgaria, Czech Republic, Estonia, Finland, Liechtenstein, Lithuania, and Slovenia in (c) due to missing observations. *Source: EIOPA (2020).*

liquid, with wide variation ranging from 19% (Germany) to 88% (Croatia).[7] Surrender payments correspond to 16% of liquid assets held by life insurers in the EU, and even 25 % of liquid assets held by life insurers in the U.S. Thus, the magnitude of surrender payments is economically significant not only relative to insurers' cash flows but also relative to insurers' liquid assets.

## 1.3 Anecdotal evidence and insurance runs

Anecdotal historical evidence highlights the link between higher interest rates, increased surrender activity, and impaired liquidity of life insurers. U.S. life insurers faced a collective rise in surrender rates when U.S. market interest rates sharply increased in the late 1970s and early 1980s. Kuo et al. (2003) report that the annual surrender rate of U.S. life insurance products increased from roughly 3% in 1951 to 12% in 1985 (while the 90-day U.S. treasury rate increased from 2% in

[7]To evaluate the market liquidity of life insurers' assets, we calculate the sum of liquid assets held by companies categorized as life insurance undertakings by EIOPA (2020). We classify the following asset classes as liquid: cash and deposits, common equity, equity and money market mutual funds, and central government, treasury, and central bank bonds. We include assets hold for unit- or index linked insurance, because they are included in the total surrender amount. Examples for illiquid assets are loans, mortgages, property and corporate bonds.

1951 to up to 15% in 1981). As a consequence, U.S. life insurers suffered high surrender costs and liquidated a large share of their asset investments (Russell et al. (2013)).

In the most extreme case, the collective exercise of surrender options resembles an *insurance run*, endangering the funding liquidity of life insurers. This occurred in the early 1990s, when several U.S. life insurers were not able to meet their liabilities due to illiquidity of their asset investments. The insurers faced a bank-run-like scenario and seven life insurers eventually failed (Brennan et al. (2013)). These *insurance runs* were mainly triggered by inadequate liquidity management. For instance, Executive Life Insurance Company and First Capital Holding Corp. invested a large share of their assets in illiquid junk bonds and securities (DeAngelo et al. (1994); Jackson and Symons (1999)), and Mutual Life Insurance Company of New York had a large real estate exposures. Notably, these runs were typically started by policyholders holding Guaranteed Investment Contracts (GICs), which are life insurance savings policies with guaranteed values and a guaranteed policy return (Brewer and Strahan (1993); Ho (2004)). GICs thus share the characteristics of modern German life insurance savings policies. Again, in 1999 rising interest rates lead to downgrades and an *insurance run* on GICs of the life insurer General American, which resulted in the life insurer's default (Fabozzi (2000)).[8]

Rising South Korean interest rates also triggered insurance runs in 1997/98. As Korean market interest rates sharply increased (by roughly 4ppt for 5-year government bonds within a few months), annualized surrender rates increased from 11% to 54.2% for long-term savings policies and life insurers' gross premium income fell by 26%. Life insurers were forced to liquidate assets, and roughly one third of Korean life insurers exited the market (Geneva Association (2012)).

## 2 Empirical analysis

In this section, we empirically document that life insurance surrender rates increase with market interest rates. Our results are consistent with policyholders reacting to interest rate hikes by surrendering more often. We causally identify this channel using an instrumental variable approach.

[8]General American distributed funding agreements with a volume of 6.5 bn USD, out of which 5 bn USD included 7-day short-term guaranteed surrender values. After rising interest rates led to large losses General American was downgraded, which resulted in widespread execution of surrender options by policyholders. The company was taken under administrative supervision and ultimately acquired by MetLife (Fabozzi (2000); Brennan et al. (2013)).

## 2.1 Data

We use the German life insurance market as an empirical laboratory. In Germany, life insurance is in general very popular and life insurance demand is comparable to other developed countries.[9] Within the German life insurance market, life insurance savings policies with annually guaranteed rates of return and guaranteed surrender values are particularly popular (see previous section).

The German financial supervisory authority (*BaFin*) publishes annual insurer-level statistics about surrender rates, premium income, investment return, and portfolio size for each German primary life insurer (i.e., excluding reinsurers). This dataset is called *Erstversichererstatistik* (i.e., *statistics on primary insurers*). It is published on BaFin's website (`www.bafin.de`) starting in 2001 and available in printed versions of BaFin's annual report in the German national library starting in 1995. We digitize the data for years from 1995 to 2010, in which the data is only available in printed or pdf format. Finally, we match insurance companies by hand over time, which results in a survivorship-bias-free panel from 1996 to 2019.[10] The panel structure allows us to include insurer fixed effects in the analyses, controlling for time-invariant insurer characteristics. In an average year, the sample comprises roughly 103 life insurers, with 2.4 trn EUR of life insurance business in force and 222 bn EUR of new business. The number of insurers, premiums and the volume of new business is relatively stable over time, while the volume of insurance in force is increasing, which suggests that the duration of insurance policies increases as well (see Figure 2).

The dependent variable in our analysis is an insurer's annual surrender rate, which is the share of policies surrendered weighted by insurance in force.[11] Before 2016, BaFin reports two surrender rates: an early surrender rate (surrender rate of new business) and a late surrender rate (other surrender as a share of the average policy portfolio in a given year). Starting in 2016, BaFin reports an overall surrender rate for an insurer's total life insurance business. In our baseline analysis, we focus on the overall surrender rate. For this purpose, we compute the overall surrender rate for years earlier than 2016 as the weighted average of the early and late surrender rate, using

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

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

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

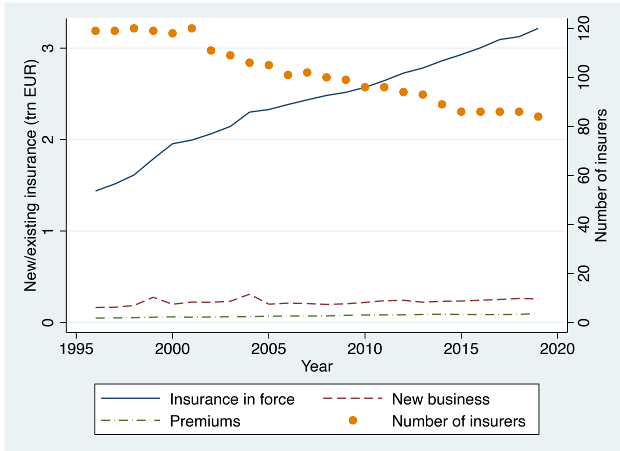



**Figure 2.** Sample size and descriptive statistics.
The figure depicts the total volume of existing insurance in place at the end of each year, premiums and the total volume of new business each year in trn EUR (left axis), and the number of insurers in each year (right axis) in the sample. Note that new business is measured by volume insured and, thus, on average exceeds premiums. *Source: Bafin Erstversichererstatistik.*

the previous year's insurance in force.[12] Therefore, data for the overall surrender rate starts in 1996. The surrender rate is 4.9% for an average insurer-year, but varies widely across insurers and years (from 0.9% to 16.4%), as reported in Table 1.[13] The share of annually surrendered life insurance policies is slightly smaller in magnitude than that of bank time deposits. For example, in a sample of Greece deposit accounts, Artavanis et al. (2019) document that, in normal times, 15% of time deposits are annually withdrawn before maturity, on average.

Our independent variable of interest is the level of market interest rates. We use the annualized yield on German government bonds with a residual maturity of 10 years since it is a widely used benchmark and available with long history.[14] Our baseline model for an insurer $i$'s surrender rate in year $t$ is

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

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

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

where insurance in $\text{force}_{t-1}$ is insurance in force at year-end $t-1$, or, equivalently, insurance in force at year-begin $t$.

[13]We winsorize the surrender rate for our regression analysis so that all values that go beyond the 99% quantile are downgraded to this value. Analogously, all values below the 1% quantile are upgraded to this value.

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

where $r_t$ is the 10-year German government bond yield, $X_{i,t}$ are insurer control variables, $Y_t$ macroeconomic control variables, and $u_i$ are insurer fixed effects. $\alpha$ is the effect of changes in the level of interest rates on surrender rates. We expect that $\alpha > 0$.

To control for the effect of insurer characteristics on surrender rates, $X_{i,t}$ includes the share of new business (relative to insurance in force at year-begin) and an insurer's investment return, capturing insurer-level trends in insurance demand and investment success, respectively. In an average insurer-year, 12.1% of an insurer's insurance in force is new business and the investment return is 5% (Table 1).

**Table 1.** Insurer-level data and macroeconomic characteristics: descriptive statistics.
Surrender rate, age, new business, and investment return are at insurer-year level retrieved from BaFin's *Erstversichererstatistik*. Remaining variables are at year level, retrieved from German Bundesbank (interest rate), BIS (inflation), OECD (GDP and investment growth), Laeven and Valencia (2018) (crisis indicator), and the German Insurance Association GDV (excess guaranteed return, new endowment, unit-linked, and aggregate business). The sample starts in 1996 and ends in 2019, and includes 163 German life insurers in total.

| | N | Mean | Median | SD | Min | Max |
|---|---|---|---|---|---|---|
| **Insurer characteristics (insurer-year level)** | | | | | | |
| Surrender rate (in ppt) | 2,263 | 4.86 | 4.47 | 2.58 | 0.90 | 16.42 |
| New business$_{t-1}$ (in ppt) | 2,237 | 12.12 | 9.55 | 11.24 | 2.19 | 30.58 |
| Investment return$_{t-1}$ (in ppt) | 2,254 | 4.98 | 4.70 | 2.03 | 2.30 | 7.60 |
| **Macroeconomic characteristics (year level)** | | | | | | |
| Interest rate$_t$ (in ppt) | 24 | 3.12 | 3.65 | 1.95 | 0.07 | 5.71 |
| Excess Guaranteed return$_{t-1}$ (in ppt) | 24 | 1.35 | 1.25 | 1.03 | -0.35 | 2.75 |
| New endowment$_{t-1}$ (in ppt) | 24 | 43.06 | 33.75 | 19.32 | 24.50 | 79.73 |
| New unit-linked$_{t-1}$ (in ppt) | 24 | 35.39 | 38.95 | 15.03 | 5.41 | 52.74 |
| New business (aggregate)$_{t-1}$ | 24 | 14.96 | 15.06 | 0.37 | 14.45 | 15.61 |
| Inflation$_{t-1}$ (in ppt) | 24 | 1.42 | 1.49 | 0.59 | 0.49 | 2.28 |
| GDP growth$_{t-1}$ (in ppt) | 24 | 3.60 | 3.67 | 2.05 | 1.49 | 6.96 |
| Investment growth$_{t-1}$ (in ppt) | 24 | -0.55 | 0.13 | 2.96 | -5.95 | 3.74 |
| Crisis$_{t-1}$ (binary) | 24 | 0.08 | 0.00 | 0.28 | 0.00 | 1.00 |
| Federal funds rate$_t$ (in ppt) | 24 | 2.42 | 1.79 | 2.27 | 0.08 | 5.87 |
| U.S. interest rate$_t$ (in ppt) | 24 | 3.85 | 3.84 | 1.47 | 1.84 | 6.35 |

Since our variable of interest, the market interest rate, is at the year-level, we cannot include year fixed effects in the baseline regression. Instead, we control for a wide range of macroeconomic characteristics that potentially affect surrender rates. In particular, we include 1-year lagged inflation (retrieved from the BIS), GDP growth and investment growth (retrieved from the OECD), and a banking crisis dummy for Germany (from Laeven and Valencia (2018)'s database). Moreover, we include information from the German Insurance Association (GDV) on the 1-year lagged new life insurance aggregate business (defined as the log of the total number of new life insurance policies), and the share of endowment and unit-linked life insurance policies (relative to the total number of life insurance policies) in Germany in each year until (including) 2019. This allows us to control for the effect of differential trends in life insurance aggregate business across policy types on surrender activity.

In additional specifications we interact $r_t$ with insurer and macro characteristics, which allows us to additionally include year fixed effects. In some of these interaction models, we use the guaranteed minimum policy return, which we proxy by the technical discount rate for German life insurance companies ("Höchstrechnungszins") in excess of the technical discount rate in 2015, which is 1.25%.[15] We also use the federal funds rate (retrieved from the Federal Reserve Bank Reports database in WRDS) and the U.S. interest rate (retrieved from the FRED St. Louis) for an instrumental variable analysis and for robustness tests, respectively.

## 2.2 Baseline results

The hypothesis is that larger market interest rates lead to larger surrender rates. Consistent with the hypothesis, in the most basic specification in Table 2 we find a highly significant and positive correlation between interest rates and surrender rates in the same year, controlling for macroeconomic characteristics and firm fixed effects (column (1)). A one-standard deviation increase in the interest rate (1.9ppt) relates to an increase in the surrender rate by roughly 0.3 standard deviations (0.8ppt). A simple back-of-the-envelope-calculation shows that this effect is economically highly significant: it corresponds to an increase by roughly 4 bn EUR in total surrender payments in Germany or, equivalently, 6% of premiums, using insurance in force reported by BaFin (2019) for 2018 as a benchmark.[16] The coefficient marginally increases in size when we lag interest rates by one year (column (2)) and decreases when we additionally control for an insurer's investment return and share of new business as well as the composition of aggregate insurance business in Germany (column (3)).

In the following specifications, we strengthen the causal interpretation of our results. First, we examine the interaction between interest rates and excess guaranteed returns for new policies. If

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

[16] The ratio of aggregate surrender payments to aggregate volume surrendered in German life insurance ranges from 14.1% to 17%, with an average of 15.5% according to BaFin's statistics from 2011 to 2019. Using the total volume of insurance in force in Germany at year-begin 2018 (3,126 bn EUR), a 1ppt increase in the surrender rate roughly corresponds to $0.008 \times 3{,}126 \times 0.155 = 3.9$ bn EUR.

**Table 2.** Interest rates and surrender rates

Fixed effects regressions of insurers' annual surrender rate on 10Y German government bond yields from 1996 to 2019. Macro controls: 1-year lagged inflation, GDP growth, investment growth, banking crises; controls for new business (aggregate): 1-year lagged aggregate life insurance business, share of new endowment and unit-linked life insurance policies in Germany. Sources: Bafin (insurer-level surrender rate, new business, and investment return), German Bundesbank (interest rate), BIS (inflation), OECD (GDP, investment growth), GDV (controls for new business), Laeven and Valencia (2018) (crisis indicator). Standard errors clustered at year and firm level. ***, **, * indicate significance at the 1%, 5% and 10% levels respectively. P-values are in parentheses.

| | (1) | (2) | (3) | (4) | (5) |
|---|---|---|---|---|---|
| Dependent variable: | | | Surrender rate | | |
| Interest rate$_t$ | 0.354*** | | | 0.308*** | |
| | (0.000) | | | (0.005) | |
| Interest rate$_{t-1}$ | | 0.366*** | 0.254*** | | |
| | | (0.000) | (0.001) | | |
| Interest rate$_t$ × Exc. Guaranteed return$_{t-1}$ | | | | -0.109** | |
| | | | | (0.037) | |
| Interest rate$_t$ × Exc. Guaranteed return$_{t-1}$ × New business$_{t-1}$ | | | | | -0.015*** |
| | | | | | (0.002) |
| Insurer FE | Yes | Yes | Yes | Yes | Yes |
| Year FE | No | No | No | No | Yes |
| Macro controls | Yes | Yes | Yes | Yes | No |
| Controls for new business (aggregate) | No | No | Yes | Yes | No |
| Inv return$_{t-1}$ | No | No | Yes | Yes | Yes |
| New business$_{t-1}$ | No | No | Yes | Yes | Yes |
| Interest rate$_t$ × New business$_{t-1}$ | No | No | No | No | Yes |
| Exc. Guaranteed return$_{t-1}$ | No | No | No | Yes | No |
| Exc. Guaranteed return$_{t-1}$ × New business$_{t-1}$ | No | No | No | No | Yes |
| No. of obs. | 2,263 | 2,255 | 2,232 | 2,232 | 2,232 |
| No. of insurers | 163 | 161 | 159 | 159 | 159 |
| $R^2$ | 0.749 | 0.749 | 0.754 | 0.756 | 0.772 |
| $R^2$ within | 0.224 | 0.220 | 0.216 | 0.223 | 0.067 |
| Standardized beta coefficients | | | | | |
| Interest rate | .26 | .27 | .19 | .22 | |

policyholders are yield-oriented, a higher guaranteed return should reduce their sensitivity towards interest rates (as in our model in Section 3.1). Consistent with this rationale, in column (4) we find that the interaction of previous year's excess guaranteed returns and current interest rates is significantly negative.

The impact of guaranteed returns for new policies should be particularly strong when relatively more policies in an insurer's portfolio are new. To test this prediction, we interact current interest rates with previous year's excess guaranteed return and the share of an insurer's new business. In column (5), we find that the coefficient on the triple-interaction term is significantly negative. This finding is consistent with the rationale that the surrender rate of insurers with a larger share of new business with a large guaranteed return is relatively less sensitive to interest rates, compared to insurers with a smaller share of new business or those with smaller guaranteed returns. Importantly, since the identifying variation in this specification comes from differential changes in the share of new business across insurers for different levels of interest rates and guaranteed returns, we are able to include both insurer and year fixed effects. Therefore, variation in the business environment of insurers (such as changes in regulation, in the overall business for life insurance, or in the macroeconomic environment) and, more generally, variation at the aggregate level is fully absorbed by year fixed effects.

Overall, the results provide strong empirical evidence that surrender rates increase relatively more with interest rates when surrender options are relatively more in-the-money. By including year fixed effects in model (5), we effectively control for the aggregate bond demand by German life insurers, addressing the potential concern that it is an omitted variable.

## 2.3 Instrumental variable analysis

A potential concern in our baseline model is that surrender rates affect bond demand by German life insurers and thereby also bond prices and market interest rates. Indeed, German insurers hold roughly 6% of outstanding German government debt securities.[17] We address this concern by including fixed effects in interaction models, which control for aggregate bond demand. However, some concerns remain as it seems possible that insurers' effect on market interest rates correlates with surrender rates.[18] To push causal identification, in this section we instrument German government bond rates with U.S. monetary policy rates.

We use the effective U.S. federal funds rate as an instrument for the German government bond rate. The first stage of our regressions shows that the instrument is relevant, as the federal funds rate strongly and positively correlates with German government bond rates (with a contemporaneous correlation coefficient of 72%). Intuitively, a tighter U.S. monetary policy (i.e., an increase in the federal funds rate) leads to an increase in U.S. government bond rates, which, by an arbitrage argument, raises German government bond rates. While the exclusion restriction is not directly testable, we argue that changes in German life insurers' surrender rates are unlikely to affect U.S. monetary policy. First, German life insurers only hold a negligible share of outstanding U.S.

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

[18] We perform a Durbin-Wu-Hausman test, which suggests that interest rates might be an endogenous variable in our baseline model. In addition, we perform a Granger causality test to analyze the existence of reverse causality between interest rates and surrender rates. The test's null hypothesis is that the information from a time series $X$ until time $t-1$ does not help to predict the times series $Y$ at time $t$. We find that interest rates Granger-cause surrender rates (p-value close to 0), while an effect of surrender rates on interest rates is borderline insignificant (p-value of 0.144).

government debt securities.[19] Thus, (the fear of) potential U.S. government sales by German life insurers are unlikely to affect U.S. monetary policy. Second, in Appendix B, we show that neither the U.S. federal funds rate nor the U.S. government bond rate has a significant effect on German surrender rates when controlling for the German government bond rate. Overall, this suggests that there is no direct effect of U.S. monetary policy on German surrender rates.

The baseline model's first stage is

$$r_{i,t} = \alpha' \cdot \text{FFR}_t + \beta' \cdot X_{i,t-1} + \gamma' \cdot Y_t + \mu'_i + \varepsilon'_{i,t},$$

where $r_{i,t}$ is the 10-year Government bond rate as before, $\text{FFR}_t$ is the annual average of end-of-month effective federal funds rates in year $t$ (retrieved from the Federal Reserve Bank Reports database in WRDS) and $X_{i,t-1}$ and $Y_t$ are insurer and macroeconomic control variables as in the baseline analysis. The results of the instrumental variable analysis are in Table 3. The first stage coefficient is highly significant, suggesting that the federal funds rate is a relevant instrument. A 1ppt increase in the federal funds rate relates to a 68bps increase in the German government bond rate, holding macroeconomic characteristics fixed (column (1)).

In the second stage, we find that interest rates have a significantly positive effect on surrender rates. The coefficient on the contemporaneous interest rates is marginally smaller than in the baseline analysis (column (1)), which is consistent with the existence of reversed causality in the baseline model. Nonetheless, the economic magnitude remains large: a one-standard deviation increase in the interest rate relates to a 26%-standard deviation increase in the surrender rate. Moreover, we find that the effect on surrender rates is marginally larger for the lagged interest rates (column (2)), that the coefficient decreases when we add further control variables (column (3)) and that higher guaranteed returns significantly reduce interest rate-sensitivity of surrender rates (column (4)). The results are consistent with the OLS estimates in the baseline analysis in Table 2. We conclude that the effect of interest rates on surrender activity is plausibly causal and consistent with yield-oriented policyholders.

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

**Table 3.** Interest rates (instrumented by federal funds rates) and surrender rates

Instrumental variable fixed effects regressions of insurers' annual surrender rate on 10Y German government bond yields from 1996 to 2019. Instruments: $FFR_t$ for models in columns (1)-(4) (1st stage effect on Interest $rate_t$ reported below), for model in column (4) also $FFR_t \times$ Exc. Guaranteed $return_{t-1}$ (1st stage effect on Interest $rate_t \times$ Exc. Guaranteed $return_{t-1}$ reported below); macro controls: 1-year lagged inflation, GDP growth, investment growth, banking crises; controls for new business (aggregate): 1-year lagged aggregate life insurance business, share of new endowment and unit-linked life insurance policies in Germany. Sources: BaFin (insurer-level surrender rate, new business, and investment return), German Bundesbank (interest rate), Federal Reserve Bank Reports database in WRDS (federal funds rate), BIS (inflation), OECD (GDP, investment growth), GDV (controls for new business), Laeven and Valencia (2018) (crisis indicator). Standard errors clustered at year and firm level. ***, **, * indicate significance at the 1%, 5% and 10% levels respectively. P-values are in parentheses.

| | (1) | (2) | (3) | (4) |
|---|---|---|---|---|
| Dependent variable: | | Surrender rate | | |
| Interest $rate_t$ | 0.351*** | | | 0.427* |
| | (0.000) | | | (0.071) |
| Interest $rate_{t-1}$ | | 0.362*** | 0.256** | |
| | | (0.000) | (0.036) | |
| Interest $rate_t \times$ Exc. Guaranteed $return_{t-1}$ | | | | -0.236* |
| | | | | (0.065) |
| Insurer FE | Yes | Yes | Yes | Yes |
| Year FE | No | No | No | No |
| Macro controls | Yes | Yes | Yes | Yes |
| Controls for new business (aggregate) | No | No | Yes | Yes |
| Inv $return_{t-1}$ | No | No | Yes | Yes |
| New $business_{t-1}$ | No | No | Yes | Yes |
| Exc. Guaranteed $return_{t-1}$ | No | No | No | Yes |
| $FFR_t$ (1st stage) | 0.680*** | 0.620*** | 0.349*** | 0.282** |
| | (0.000) | (0.000) | (0.000) | (0.013) |
| $FFR_t \times$ Exc. Guaranteed $return_{t-1}$ (1st stage) | | | | 0.424*** |
| | | | | (0.002) |
| Cragg-Donald Wald F Statistic | 4917.4 | 5565.2 | 1838.2 | 372.7 |
| No. of obs. | 2,263 | 2,255 | 2,232 | 2,232 |
| No. of insurers | 163 | 161 | 159 | 159 |
| Standardized beta coefficients | | | | |
| Interest rate | .26 | .26 | .19 | .31 |

# 3 Surrender risk and financial fragility

In this section, we develop a model to quantify the economic importance of surrender risk for liquidity risk of life insurers and financial markets. Section 3.1 presents the model and calibrates it to the balance sheet and cash flows of an average German life insurer in 2015.[20] We present the baseline results in Section 3.2 and assess the sensitivity of the results in Section 3.3.

## 3.1 Model

We model life insurers' key business activities that result in an exposure to surrender and liquidity risk and the transmission to financial markets. The insurer sells life insurance policies and invests the proceeds in financial assets. If many policyholders surrender, the insurer is forced to sell assets, which affects market prices. Below we provide a broad overview of the model ingredients,

[20]Since interest rates were low in 2015, from the perspective of an insurer's balance sheet, this year represents a reasonable starting point to assess the effects of rising interest rates. Nonetheless, we neither make a statement about the likelihood nor adequacy of rising interest rates in 2015 from a macroeconomic perspective, which would by far exceed the scope of this paper.

and discuss more details in the Online Appendix C.

**3.1.1 Insurance policies.** Our model picks up the main features of life insurance policies, which are shared across many jurisdictions worldwide. Specifically, policies are long-term and they annually return the maximum of a fixed guaranteed minimum return and the return on underlying asset investments. For computational simplicity, we entirely focus on policies' savings phase: policyholders annually invest $P$ in their policy and receive a lump-sum payment at contract maturity.[21] Each year, each policyholder may surrender her policy, upon which the insurer pays out her policy's cash value, i.e., policy return accumulated in previous years, less a surrender penalty.

The aggregate cash value of policyholder cohort $h$ evolves according to

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

where $V_{t+1}^h$ is the cash value at year-end $t+1$, $h$ is the policy cohort indicating the first year of investing in the policy, $\tilde{r}_{P,t+1}^h$ is the policy return which is credited at year-end $t+1$, $P$ is the annual premium that each policyholder invests each year, and $N_{t+1}^h$ is the number of policyholders at year-end $t+1$. $V_{t+1}^h$ corresponds to the account value of the insurer's liabilities according to German historical cost accounting. The share $\lambda_{t+1}^h$ of previous year's policyholders $N_t^h$ surrenders at year-begin $t+1$, and thus $N_{t+1}^h = (1 - \lambda_{t+1}^h) \cdot N_t^h$. When a policy matures at year-end $T^h$, $V_{T^h}^h$ is paid out to the remaining policyholders.[22]

$\lambda_{t+1}^h$ is the surrender rate, i.e., the share of policyholders that surrenders at year-begin $t+1$, and $SV_t^h$ is a policy's surrender value, which is paid out upon surrender. As it is common for life insurance policies, the surrender value depends on the policy's current cash value $V_t^h$ but deducts a relative surrender penalty $1 - \vartheta$, $\vartheta \in (0,1)$.[23] Consistent with the timing in the model, we specify that a policyholder of cohort $h$ is paid $SV_t^h = \vartheta \frac{V_t^h}{N_t^h}$ upon surrender at year-begin $t+1$, i.e., the surrender value at year-begin $t+1$ is based on the cash value at year-end $t$.

[21] Many life insurance policies also allow to transfer the lump-sum payment to an annuity contract, providing the policyholder with a pre-defined payment stream. Nonetheless, many studies find that policyholders rarely annuitize a large fraction of their wealth, which is often referred to as the *annuity puzzle* (see, e.g., Mitchell and Moore (1998) and Brown (2001)).

[22] Note that policies within cohorts are homogeneous and, thus, each policy's cash value is $V_t^h/N_t^h$.

[23] This convention is, e.g., followed by German insurance law (Section 169) and the U.S. National Association of Insurance Commissioner's model law (NAIC (2017)).

To model the evolution of policies' cash value, we are left with specifying the dynamics of the policy return and surrender rate. We present a model for surrender decisions on the policyholder level in the next section, which determines the annual surrender rate. The policy return is given by

$$\tilde{r}^h_{P,t+1} = \max\{r^h_G,\, \tilde{r}^*_{t+1}\}. \tag{2}$$

Here, $r^h_G$ is the minimum annually guaranteed return of return (*guaranteed return* hereafter), which is fixed at contract inception $t = h$ for the entire policy life, and $\tilde{r}^*_{t+1}$ is the investment return. Motivated by life insurer insolvencies in the 1980s and 1990s, regulators (especially in Europe and Japan) set (explicit and implicit) maximum levels for guaranteed returns which depend on long-term interest rate averages (Grosen and Jorgensen (2002)). Following German life insurance regulation, we assume that $r^h_G$ is annually adjusted and tracks 60% of the 10-year moving average of 10-year German sovereign bonds at time $t = h$ in 50bps steps (Eling and Holder (2012)).[24]

Due to their dominance in the European life insurance market (see previous section), we focus on participating policies. Thus, all of the insurer's funds are invested at the life insurer's discretion.[25] Policyholders receive a fraction $\xi \in (0, 1)$ of the insurer's total investment income if this exceeds the guaranteed return,[26]

$$\tilde{r}^*_{t+1} = \xi \frac{R^a_t}{\sum_{h=1}^{H} V^h_{t-1}}. \tag{3}$$

**3.1.2 Surrender decisions.** Motivated by the empirical analysis in Section 2, we model each policyholder's surrender decision as a function of the (1) market interest rate, (2) policy return $\tilde{r}^h_{P,t}$,

[24]German law explicitly specified 60% of the 10-year yield on AAA-rated European sovereign bonds as the cap of the guaranteed return until 2015 (§65 VAG). Since 2015 the calculation of the cap is not specified any more (§88 VAG). However, German regulators did not deviate much from the 60% rule. For example, our model predicts that the guaranteed return would by lowered in 2017 if interest rates were not increasing by much, which is exactly what the German regulator did in 2017. Although German insurers are allowed to offer policies with a guaranteed return lower than the regulatory cap, they never do so.

[25]This form of delegated asset investment is common in many jurisdictions. Assets for participating policies appear on the insurer's *general account*, while assets for non-participating (i.e., unit- or index-linked) policies appear on the *separate account*. Separate accounts are typically small as a share of life insurers' total assets, e.g., 10% in Germany and 38% in the U.S. in 2015 (*Sources: BaFin Erstversichererstatistik, FED Z.1 Flow of Funds*).

[26]The investment income $R^a_t$ includes fixed income coupon payments, stock dividends, and rents less depreciations on the insurer's GAAP (historical cost) balance sheet (it excludes unrealized market value gains). We abstract from insurers' ability to smooth the distribution of asset income over time, which is discussed by Hombert and Lyonnet (2019).

and (3) contract age.[27]

Consider a policyholder at the beginning of year $t$ who owns a life insurance savings policy that was purchased at the end of year $h$, $h < t$. The insurance policy's current cash value is $v^h_{t-1} = V^h_{t-1}/N^h_{t-1}$ and its surrender value is $SV^h_{t-1}$, both based on year-end $t-1$. Without loss of generality, we assume that policyholders pay accumulated fees (to cover administrative costs) at the earlier of surrender and maturity date. Cumulative fees are a share $1 - e^{-c(t-h-1)}$ of the policy payout, where $c(\cdot)$ is a non-negative and increasing function of the policy age $t-h-1$.[28] Thus, the surrender value net of (administrative) fees is $SV^h_{t-1}e^{-c(t-h-1)}$.

Surrendering the policy results in additional (relative) transaction costs $\mathcal{G} > 0$ for the policyholder. For instance, the policyholder loses the possibility of converting the policy into an annuity at maturity, and must undertake time-consuming effort to surrender. Transaction costs may be (partly) offset by the value of satisfying policyholders' liquidity needs $\mathcal{L} > 0$ (e.g., arising from unemployment, medical expenses, or new consumption opportunities), such that the final value of surrendering is $SV^h_{t-1}e^{-c(t-h-1)}e^{\mathcal{L}-\mathcal{G}}$. Below, we allow for heterogeneity in $\mathcal{L} - \mathcal{G}$ across policyholders.

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

$$SV^h_{t-1}e^{-c(t-h-1)}e^{\mathcal{L}-\mathcal{G}} > \mathcal{M}^h_{t-1}e^{-c(T^h-h)}, \tag{4}$$

where $\mathcal{M}^h_{t-1}e^{-c(T^h-h)}$ is the net (of fees) present value of holding the life insurance policy until maturity $T^h$.[29] We assume that policyholders extrapolate future policy returns using the current policy return, implying that $\mathcal{M}^h_{t-1} = v^h_{t-1}\left(\frac{1+\tilde{r}^h_{P,t-1}}{1+r_{f,t-1,T^h-(t-1)}}\right)^{T^h-(t-1)}$, where $r_{f,t-1,T^h-(t-1)}$ is the risk-free rate in year $t-1$ for maturity $T^h-(t-1)$, proxied by the respective German government bond yield. This assumption is consistent with the observation that life insurers mainly compete

[27] For a discussion about the challenges of modeling policyholder behavior with respect to surrender decisions, we refer to Bauer et al. (2017).

[28] We use the convention of assigning at year-begin $t$ an age of zero to a policy that was initiated (bought) at year-end $t-1$.

[29] We stress that this model does not necessarily reflect the *optimal* exercise of a surrender option (as, e.g., in Förstemann (2019)). Instead, our goal is to formulate a model that is motivated by our empirical analysis in Section 2 and that can be calibrated with existing empirical data. This approach is also warranted by Hambel et al. (2017)'s result that a calibrated rational-expectations life-cycle model produces much lower term life insurance surrender rates than empirically observed.

over policy returns in practice.[30]

The decision to surrender in Equation (4) is equivalent to

$$\mathcal{L} - \mathcal{G} > \log \frac{\mathcal{M}_{t-1}^h}{SV_{t-1}^h} - \Delta c_t, \tag{5}$$

where $\mathcal{L} - \mathcal{G}$ is the liquidity need relative to transaction costs, and the right hand side is the value of the policy's payout at maturity relative to its surrender value less of future fees $\Delta c_t = c(T^h - h) - c(t - h - 1)$.[31] The relative policy value equals

$$\frac{\mathcal{M}_{t-1}^h}{SV_{t-1}^h} = \vartheta^{-1} \left( \frac{1 + \tilde{r}_{P,t-1}^h}{1 + r_{f,t-1,T^h-(t-1)}} \right)^{T^h-(t-1)}, \tag{6}$$

and is thus driven by the difference in policy return $\tilde{r}_{P,t-1}^h$ and risk-free rate $r_{f,t-1,T^h-(t-1)}$.

Annual fees for life insurance policies are typically decreasing with policy age. Decreasing marginal fees imply that $c(\cdot)$ is concave, $c''(\cdot) < 0$.[32] We assume that $c(x) = k \log(2 + x)$ with $k > 0$ for policy age $x = t - h - 1 \geq 0$. Equation (5) implies that smaller future policy fees $\Delta c_t$, resulting from high policy age, reduce the incentive to surrender. A smaller surrender rate for older policies is consistent with empirical evidence (e.g., Belth (1968); Cerchiara et al. (2009); Milhaud et al. (2010); Eling and Kiesenbauer (2014)).

If $\mathcal{L} = \mathcal{G}$ and $\Delta c_t \equiv 0$, the model boils down to a comparison between a policy's present value and surrender value. Instead, heterogeneity in surrender incentives enables us to calibrate the model to empirically observed surrender rates. For this purpose, we make the simplifying assumption that $\mathcal{L} - \mathcal{G}$ is normally distributed across policyholders, with expected value $\mu_L$ and variance $\sigma_L^2$ independently across policyholders and time. Then, the probability that a randomly

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

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

[32] German life insurers must deduct fees from surrender values evenly distributed across a policy's first 5 years (see German Insurance Contract Law, Section 169).

selected policyholder in cohort $h$ surrenders is given by

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

which is the surrender rate in cohort $h$ in year $t$. We calibrate $\beta_0, \beta_1$, and $\beta_2$ as described in Appendix C.1 by using the data described in Section 2.

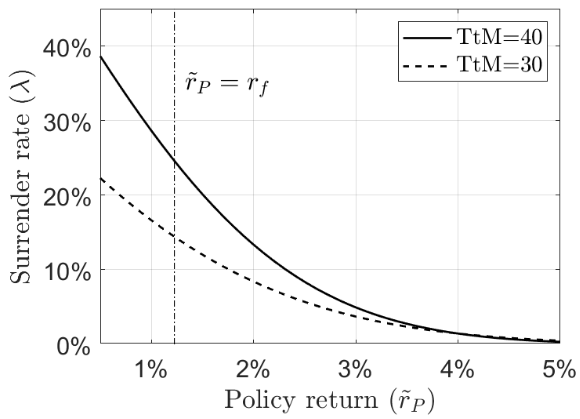



**Figure 3.** Surrender rate calibration.
The figure depicts the likelihood for a random policyholder to surrender a 40-year policy with current policy return $\tilde{r}_P$ and time to policy maturity, $TtM$, of 30 and 40 years. In the figure, we assume a flat risk-free rate of $r_f = 1.22\%$, corresponding to the 10-year German sovereign bond yield in 2015, and surrender penalty $\bar{\vartheta} = 1 - \vartheta = 2.5\%$.

The resulting calibration is illustrated in Figure 3. Surrender rates are monotonically declining with the policy return since a higher policy return increases the opportunity cost of surrendering, relative to a fixed market interest rate. Surrender rates increase with remaining time to maturity (i.e., decrease with age) since (1) future policy fees $\Delta c_t$ become smaller and (2) the interest rate sensitivity of the present value of future policy cash flows, $\mathcal{M}_{t-1}^h$, declines with shorter time to maturity. The pattern and level of surrender rates is consistent, e.g., with empirical evidence from Gottlieb and Smetters (2016).

Surrendering policyholders consume a part of the surrender payout (e.g., to satisfy liquidity needs) and may invest the remainder on financial markets.[33] We assume that policyholders do not invest in the same assets that the insurer invested in.

[33] Assuming that the decision to buy life insurance is based on observed policy returns, it is not optimal for policyholders to reinvest in a new life insurance policy upon surrender.

### 3.1.3 Balance sheet and portfolio allocation.

**3.1.3 Balance sheet and portfolio allocation.** The insurer's policy portfolio consists of several cohorts, i.e., generations of insurance policies. Each year, the insurer sells a fixed number of new policies $N$ and collects the premium $P$ (net of fees) for each existing policy.[34] Without loss of generality, we assume $P = 1$ and $N = 10,000$.

Consistent with the long lifetime of life insurance policies, policies in our model have a total lifetime of $T^h - h = 40$ years but differ according to age and (potentially) the guaranteed return across cohorts. Cohort $h$ consists of all non-surrendered insurance policies that were sold in year $h$.

At the starting point of our model (the end of year $t = 0$, calibrated to 2015), the insurer's portfolio features 40 cohorts. The oldest cohort $h = -39$ was sold at year end $t = -39$ (i.e., 1976) with guaranteed return $r_G^{-29} = 3\%$, and the latest was sold in $t = 0$ (i.e., 2015) with $r_G^0 = 1.25\%$, in line with the historical evolution of $r_G^h$ in Germany. To compute the initial distribution of cash values across cohorts, $V_0^h, h = -39, ..., 0$, we draw on the historical evaluation of annual premiums written on new life insurance policies, average surrender rates and policy returns in Germany. We extrapolate where needed and adjust the relative size of cohorts to match key characteristics of German life insurers in 2015, as described in Online Appendix C.2. The resulting initial policy portfolio features an average policy return of 2.68% per policy (see Table 4), which is consistent with Assekurata Cologne (2016) reporting an average guaranteed return of 2.97% for German life insurers in 2015. Moreover, the initial portfolio exhibits a modified duration of roughly 14.1 years, which coincides with the median liability duration of German life insurers according to the German Insurance Association (2015).

| **Variable** | **Calibration** |
|---|---|
| Average surrender rate | 2.97% |
| Average guaranteed return (per policy) | 2.68% |
| Avrg. remaining policy lifetime | 29.57 |
| Equity capital / assets | 9% |
| Modified Duration (Liabilities) | 14.41 |
| Modified Duration (Assets) | 9.39 |

**Table 4.** Initial calibration of the insurer's balance sheet.

The insurer invests in four different asset classes: (1) German, French, Dutch, Italian, and

[34] Time-varying demand is implicitly captured by policyholders' ability to surrender policies in the first year after purchase.

Spanish sovereign bonds, (2) AAA, AA, A, and BBB-rated corporate bonds, (3) German, French, Dutch, Italian, and Spanish stocks and (4) real estate. This detailed modeling of the insurer's investment portfolio is important to calibrate investment return dynamics (which determine the policy returns, as in Equation (3)). The relative weight (in market values) and duration of each asset class are calibrated based on German Insurance Association (GDV) (2016) and EIOPA (2014, 2016).

The resulting portfolio allocation is reported in Table 5.[35] The overall duration is consistent with reports by the German Insurance Association and Assekurata Cologne (2016). Fixed income is the largest investment class, consistent with other jurisdictions such as the U.S. (McMenamin et al. (2013)). The allocation of fixed income assets across ratings is skewed toward higher-rated assets, consistent with the distribution across ratings reported by Assekurata Cologne (2016). During the evolution of the model, we assume that relative portfolio weights remain constant in terms of market values. This investment strategy is plausible for insurers to maintain a similar level of investment risk and asset duration over time.

| **Entire Investment Portfolio** | **Weight** | **Target Modified Duration** |
|---|---|---|
| Sovereigns $w_{\text{sov}}$ | 55.3% | 10.4 |
| Corporate $w_{\text{corp}}$ | 34.1% | 7.5 |
| Stocks $w_{\text{stocks}}$ | 6.7% | - |
| Real Estate $w_{\text{real estate}}$ | 3.9% | - |

**Table 5.** Investment portfolio allocation.
The table depicts the weights and average modified duration of each asset class in the insurer's investment portfolio. The calibration is based on EIOPA (2014, 2016) and German Insurance Association (GDV) (2016) as described in Online Appendix C.3.

All bonds are purchased at par and pay annual coupons. Bonds differ by the time of purchase, such that within each bond category the oldest bond is due in 1 year and the youngest in 20 (10) years.[36] 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 a current year's price change in the national stock and real estate index, respectively.

Given the investment portfolio weights, insurance policy portfolio, and asset prices (as implied by the financial market model described in the next section) at time $t = 0$, we determine the size of

[35] Sub-portfolio weights and the detailed calibration procedure are reported in Online Appendix C.3.
[36] Weights within bond categories across years of purchase are determined in order to match the bond category's overall duration.

total assets (at market value) according to a fixed initial equity capital ratio of 9%. This assumption is motivated by EIOPA (2016), who report 8.8% equity capital relative to total assets for German life insurers in January 2016.[37] It is also consistent with the ratio of market equity to total assets of listed European life insurers in 2015.[38] The resulting initial calibration, as reported in Table 4, closely matches the balance sheet of German life insurers in 2015. Supporting our calibration of the insurer's allocation, our model predicts an average investment return of 2.9% for 2016 ($t = 1$), which closely matches the average investment return of German life insurers in 2016 (3.04% as reported in BaFin's *Erstversichererstatistik*).

**3.1.4 Interest rates and stochastic financial market.** We use a stochastic financial market model to simulate (1) increasing market interest rates, (2) bond spreads, and (3) stock and real estate returns. Short rates evolve according to Hull and White (1990)'s model and drive the evolution of risk-free interest rates.[39] Short rate dynamics are

$$dr(t) = \alpha_r(\theta_r(t) - r(t))dt + \sigma_r dW_r(t), \tag{8}$$

where $r(t)$ is the short rate at time $t$, $W_r(t)$ is a standard Brownian motion, $\alpha_r > 0$ the speed of mean reversion, $\sigma_r > 0$ the volatility, and $\theta_r(\cdot)$ a function for the level of mean reversion. Under the assumption of arbitrage-free interest rates, Equation (8) specifies the term structure of annually compounded risk-free interest rates at time $t$ for maturities $\tau$, $\{r_{f,t,\tau}\}_{\tau \geq 0}$. In order to simulate rising interest rates, we explicitly specify $\theta_r(\cdot)$ as an increasing function given by[40]

$$\theta_r(t) = \gamma + (\beta - \gamma)\left(1 - \frac{1}{1 + e^{-bt}}\right), \tag{9}$$

[37] Specifically, EIOPA (2016, Figure 10) report that total assets divided by total liabilities is 109.5% for a large sample of German insurers (that have 75% market share) that consists almost entirely of life insurers, which corresponds to a capital ratio of 8.8%. Since we largely follow EIOPA's approach to quantify life insurance liabilities, this capital ratio is adequate for calibration in our model.

[38] 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.

[39] We treat German interest rates as risk-free, motivated by its AAA rating and safe haven status on financial markets.

[40] $\beta$ and $\gamma$ are the initial and long-term levels of mean reversion, respectively, and $b$ describes the skewness of the mean reversion level over time.

which we calibrate as described in Online Appendix C.4. The resulting interest rate environment displays a gradual long-term increase in interest rates, during which the median risk-free rate with a maturity of 10 years (*10-year risk-free rate* hereafter) starts at roughly 0.5% in $t = 0$ and increases on average by roughly 22bps each year (see Figure 4). This pace of increase is plausible and relatively moderate: the average increase in 10-year German government bond yields from 1973 to 2020 was 71bps, the median 56bps.[41]

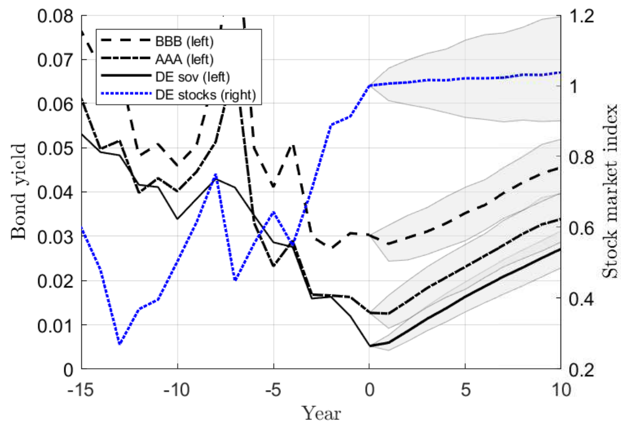



**Figure 4.** Financial market dynamics: historical and simulated.
The figure depicts the median and 25th / 75th percentiles of 10-year simulated (a) German government bond, (b) AAA, and (c) BBB bond yields, and (d) German stock market index from year 0 on. Prior to year 0, we show the actual historical evolution, up to year 0 which corresponds to 2015. Thereby, AAA and BBB yields are defined as the sum of 10-year German government bond yield and the spread of the AAA- and BBB-subset of the ICE BofAML U.S. Corporate Master Index relative to 10-year U.S. treasury rates (obtained from *FRED St. Louis*).

Spreads for sovereign and corporate bonds follow Ornstein-Uhlenbeck processes and stocks and real estate indices follow Geometric Brownian Motions. The calibration is based on bond yields, national stock and real estate indices on a monthly basis from January 1999 to December 2007.[42]

**3.1.5 Fire sales.** At the end of each year $t$, (1) the insurer pays out surrendered policies based on last year's surrender values, (2) financial market and investment returns realize, (3) policy returns are credited to non-surrendered policies, (4) active (i.e., non-surrendered and non-maturing) policyholders pay premiums, (5) a new policy cohort (given the current guaranteed return) is sold, (6) the insurer's free cash flow realizes. The free cash flow is the difference between cash inflow

[41]We stress that it is beyond the scope of this paper to discuss the plausibility of an interest rate rise from a macroeconomic perspective.

[42]We choose a time period before 2007 to capture high and low levels of interest rates. The data used for calibration as well as the detailed calibration procedure are described in Online Appendix C.5.

(premiums, fixed income coupon and principal payments, dividends, and rents) and cash outflow (maturing and surrendered policies).

If the free cash flow is negative, the insurer liquidates assets (maintaining portfolio weights at market values).[43] Consistent with a recent literature that documents the importance of institutional investors to absorb financial market supply and demand shocks (Ellul et al. (2011, 2015), Koijen and Yogo (2019)), we expect that asset liquidations by insurers - following a negative free cash flow - depress financial market prices.[44] As our results will show, the free cash flow becomes negative when an interest rate rise triggers large surrender activity. Since the effect of interest rates on insurers' free cash flow correlates across insurers, they are indeed collectively forced to liquidate assets.

We quantify fire sale costs and price externalities arising from surrenders, treating the insurer in our model as representative for (part of) the life insurance sector and, thus, $\max(-FCF_t, 0)$ as the life insurance sector's total liquidity need. If there was no price impact of asset sales, the volume of asset sales EUR $s_t$ (in market values before accounting for fire sale costs) would equal insurers' liquidity need, $s_t = \max(-FCF_t, 0)$. However, if assets' liquidation value is subject to a fire sale discount $\delta s_t > 0$ upon selling $s_t$, the volume of asset sales $s_t$ is

$$\max(-FCF_t, 0) = s_t(1 - \delta s_t) \;\Leftrightarrow\; s_t = \frac{1 - \sqrt{1 - 4\delta \max(-FCF_t, 0)}}{2\delta}. \tag{10}$$

Equation (10) reflects the contagious effect of fire sales: the more assets $s_t$ insurers sell, the higher the price discount $\delta s_t$ at which the assets trade, and the more assets $s_t$ insurers must sell in order to meet their liquidity need.[45]

Insurers sell $s_t$ (at fair value) but only receive $\max(-FCF_t, 0)$, implying that fire sale costs are

[43] It is beyond the scope of this paper to calibrate a more detailed asset liquidation strategy. The assumption of proportional asset liquidation is common in the literature (e.g., Greenwood et al. (2015) and Ellul et al. (2020)). Since surrender payments substantially exceed their financial liabilities (surrender payments of European insurers are 6.3 times the volume of their financial liabilities owed to credit institutions (excluding bonds); *Source:* EIOPA (2020)), it seems unlikely that insurers fund surrender payments by capital market financing.

[44] This rationale is consistent with empirical studies that document the price impact of insurers' asset trading (e.g., Ellul et al. (2011, 2015), Girardi et al. (2018)). Due to the substantial size of life insurers as well as high correlation of their trades (Girardi et al. (2018); Chiang and Niehaus (2020)), collective asset liquidations can result in fire sales. This rationale is analogous to fire sales due to (active) de-leveraging by banks (Greenwood et al. (2015)) or insurers (Ellul et al. (2020)). It however differs to the extent that fire sales in our model are the result of a negative free cash flow (i.e., forced by surrender activity) and not the result of insurers aiming for lower leverage.

[45] If $1 - 4\delta \max(-FCF_t, 0) < 0$, no solution to the fire sale spiral exists, implying that insurers are not able to receive the desired cash in order to satisfy their liquidity need. Then, fire sale costs result in insolvency. This case occurs if assets are sufficiently illiquid and the liquidity need sufficiently large (i.e., with large $\delta$ and $\max(-FCF_t, 0)$).

$s_t - \max(-FCF_t, 0)$.[46] The price impact of fire sales is $\delta s_t$, which is a measure for the externality generated by fire sales on other institutions.[47]

To calibrate $\delta$, we follow Greenwood et al. (2015) and assume that every 10 bn EUR asset sale leads to a price reduction by 10bps. This calibration is consistent with the price impact of U.S. insurers' fire sales after corporate bond downgrades (Ellul et al. (2011)). We assume that the price impact in one particular year is absorbed during the following year.[48]

We scale the insurer's balance sheet to estimate the total life insurance sector's liquidity need and fire sale costs, focusing on European life insurers. Since life insurers do not only sell savings policies with financial guarantees (but, e.g., also term life insurance and immediate annuities), taking the total life insurance sector as reference point would likely overestimate fire sale costs. Instead, we exclude health, unit- and index-linked policies and policies without surrender options by scaling the insurer's insurance reserves to 80% of European life insurance reserves excluding health, unit- and index-linked policies in 2016 Q3.[49] Thus, we focus on policies that feature the same characteristics as the one in our model (German life insurance reserves are roughly 19% of that of all European insurers (EIOPA (2020))).

## 3.2 Results

**3.2.1 Slow pass-through of interest rates.** In the following, we describe the results of our simulation, based on 1,000 financial market and surrender decision paths with a length of 10 years. Figure 5 (a) depicts the evolution of market interest rates, the insurer's investment and policy

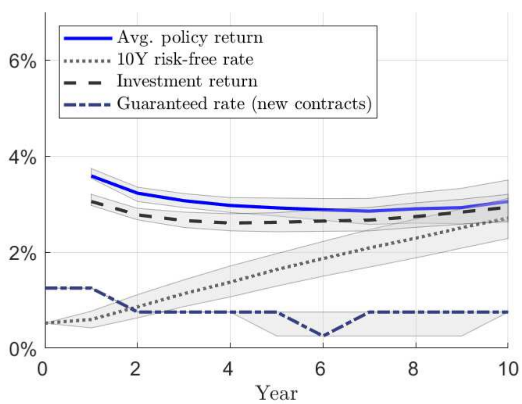
[46] It is straightforward to show that $s_t > \max(-FCF_t, 0)$ if, and only if $\delta > 0$, and $s_t = \max(-FCF_t, 0)$, otherwise. Thus, fire sale costs are non-negative.

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

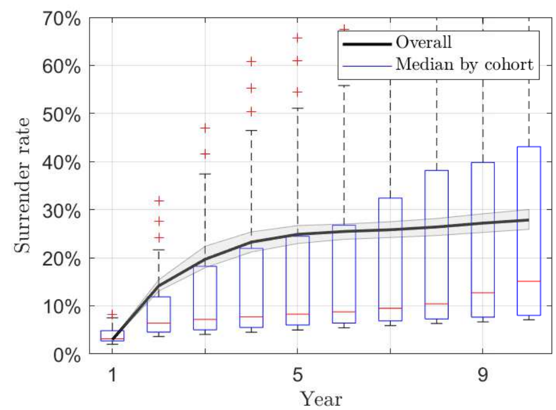
[48] This assumption is in line with empirical evidence from Newman and Rierson (2003), who estimate that the price impact associated with a 16 bn EUR bond issuance by Deutsche Telekom was 10bps on the same day, but quickly phased out of the market in the subsequent days. The assumption is also consistent with Ellul et al. (2011)'s results, who find that the price impact of insurers' fire sales upon bond downgrades vanishes after at least 30 weeks.

[49] While our model is calibrated to 2015, the earliest available details on European life insurance reserves at market-consistent (Solvency II) accounting reported by EIOPA (2020) are from the third quarter of 2016. Since the volatility of European life insurance reserves over time is very low (the standard deviation of quarterly EU life insurance reserves between 2016 Q3 and 2018 Q1 is roughly 2% relative to 2016 Q3), we use the value from 2016 Q3 to calculate fire sale costs, which implies 5.238 trn EUR life insurance reserves excluding health and unit- and index-linked. The scaling factor is conservative for two reasons: (1) insurers may also have to liquidate assets when unit- and index-linked policies are surrendered (which we nonetheless exclude because surrender dynamics may be different than in our model), and (2) we likely underestimate the share of liabilities that can be surrendered: EIOPA (2019) reports that only 12% of European life insurance reserves for life insurance with profit participation have no surrender option and that only 22% are subject to a surrender penalty.

returns. As prescribed by the financial market model, the 10-year market risk-free rate (proxied by the German government bond yield) gradually increases by roughly 22bps per year. However, the insurer's investment return decreases. The reason is the insurer's assets long duration and declining interest rates in the past. Old long-term bonds with high yields are gradually replaced by new bonds with increasing but relatively lower yields. Given a modified duration of 9.4 years, it takes roughly the same time until the average bond yield in the insurer's investment portfolio increases.




(a) Interest rates, investment and policy return.




(b) Surrender rates.

**Figure 5.** Interest rates, policy returns, and surrender rates.
Figure (a) depicts the market interest rates, the guaranteed return for new policies, the insurer's investment return, and policy returns in each year (median and 25th / 75th percentiles). Figure (b) depicts the share of surrendered policies in each year (median and 25th / 75th percentiles; straight lines) and the distribution of each cohort's median surrender rate across cohorts (boxplots).

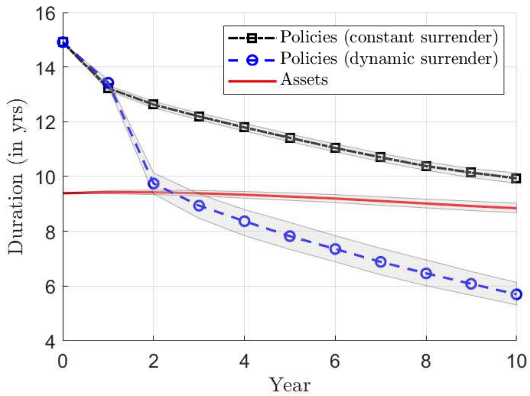
Figure 5 (a) vividly illustrates that policy returns closely follow the insurer's investment return. This is intuitive during an interest rate rise since existing policies have relatively low guaranteed returns due to low current market interest rates and, thus, are not binding. Therefore, the slow pass-through of higher interest rates to the insurer's investment return then translates into a slow pass-through of higher interest rates to policy returns. Guaranteed returns for new policies also decline during the interest rate rise. The reason is that, similarly to the insurer's investment return, they are based on a moving average of previous years and, therefore, mostly driven by previously declining rates.

Resulting from these return dynamics, the gap between policy return and market interest rate, i.e., the *excess* policy return, shrinks. Consistent with our empirical results in Section 2, surrendering a policy then becomes relatively more attractive. Our model predicts that surrender rates increase with the decline in the *excess* policy return - from an average rate of roughly 3% at model begin to almost 30% after 10 years of rising interest rates. We report the annual surrender rate (as a share of existing policies) in Figure 5 (b). This level of surrender rates is large but still plausible, as our empirical analysis in Section 2 shows. The marginal increase is largest during the first years of the interest rate rise, during which the insurer's investment returns and policy returns are decreasing.

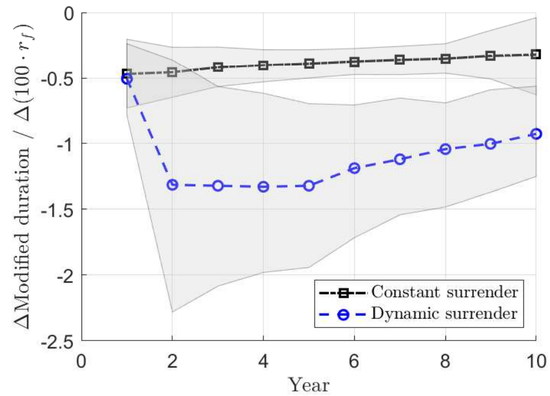
**3.2.2 Interest rate convexity.** The interest rate sensitivity of surrender activity has two main effects: (1) it reduces the duration of insurance policies and (2) it reduces an insurer's free cash flow during an interest rate rise. The first effect leads to convexity of life insurance policies. Rising interest rates then not only reduce the present value of future policy cash flows by increasing the discount factor but also by moving cash flows to earlier years. An additional effect comes from portfolio dynamics: maturing policy cohorts are substituted by relatively younger cohorts. Since maturing cohorts benefited from large policy returns at a young policy age (especially in years before 2005), their weight in the policy portfolio is large relative to the weight of cohorts at the same age but that were sold later. Thus, upon maturity of these cohorts with large cash values, the *average* duration across policies further decreases.

To disentangle the two effects, we compare our results to a counterfactual calibration in which surrender rates are constant to the initial surrender rate ($\bar{\lambda} \equiv 2.97\%$) across policyholders and time. We interpret the counterfactual calibration as a situation in which policyholders only surrender due to idiosyncratic liquidity needs. We find that in this counterfactual calibration, the duration of life insurance policies is decreasing (Figure 6 (a)). This is consistent with the portfolio dynamics described above, namely that the relative share of policies with a relatively large cash value declines over time. The average modified duration of the policy portfolio declines from 14 years at $t = 0$ to roughly 10 years at $t = 10$.

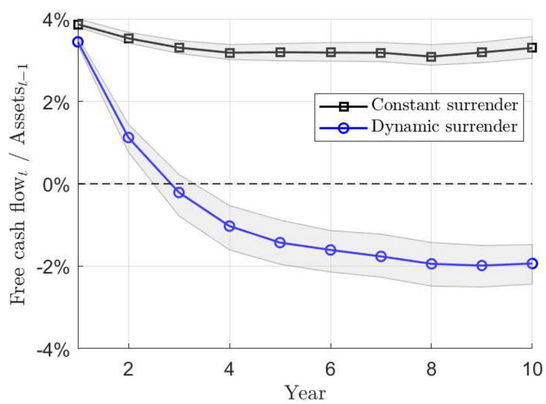
The reduction in policy duration during an interest rate rise is substantially larger when surrender rates are interest rate sensitive, as in our baseline calibration. In this case, the modified duration shrinks from 14 years at $t = 0$ to roughly 6 years at $t = 10$. Part of this dynamic is explained by portfolio dynamics *across* policies (see the case with constant surrender rate). The




(a) Modified duration.




(b) Interest rate sensitivity of duration.




(c) Free cash flow.

**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 policy portfolio if each policyholder's surrender rate is fixed at 3.58% (squares), and of the insurer's policy portfolio if surrender rates depend on policy age, return and market interest rates (circles). Figure (b) depicts the (median and 25/75 percentile) change in the life insurance policy portfolio's modified duration for a 1ppt change in the 10-year risk-free rate. We estimate this sensitivity for each year by the deviation in modified duration from its annual median for a 1ppt deviation in the 10-year German sovereign bond yield from its annual median. Figure (c) depicts the insurer's free cash flow relative to the previous year's total assets for the same two calibrations. We show the median and 25th / 75th percentiles in each year.

difference to the case with a constant surrender rate is due to the effect of a re-distribution of cash flows *within* policies: policyholders are more likely to surrender earlier than later. Due to this interest rate sensitivity of surrender rates, the modified duration of policies falls by additional 4 years and even below the duration of the insurer's assets (which is at roughly 9 years over the whole time horizon). Therefore, interest rate sensitivity leads to convexity in life insurance policies: policy duration shrinks with rising interest rates. Importantly, due to convexity a gradual but long-lasting interest rate rise can reverse the direction of interest rate sensitivity of life insurers' equity. Starting with a negative duration gap (larger policy than asset duration), i.e., a long position in market interest rates, the duration gap becomes positive after 3 years in our model. Then, insurers have a short position in market interest rates, i.e., the market value of insurers' equity increases with decreasing interest rates.

To disentangle portfolio effects from convexity, we compute the sensitivity of the life insurance policy portfolio's modified duration toward interest rate changes *within* years. This is the deviation in modified duration from its annual median for a 1ppt deviation of the 10-year risk-free rate from its annual median, which we depict in Figure 6 (b). When the surrender rate is constant, a 1ppt increase in the risk-free rate relates to a roughly 5 months decrease in the modified duration. This baseline convexity is due to the non-linear relationship of price and yield. The convexity is much larger when surrender rates are dynamic. In this case, we estimate that a 1ppt increase in the risk-free rate relates to an increase in the duration by roughly 1.3 years. Thus, surrender options with guarantees lead to substantial convexity even in the absence of portfolio dynamics. For a 22bps increase in interest rates (which roughly corresponds to the annual change in the 10-year rate in our model) the estimate in Figure 6 (b) roughly implies a 3 month decline in modified duration. Portfolio dynamics further amplify this decline, as old cohorts with large cash values are replaced by young cohorts with relatively smaller cash values. As a result, the actual annual decline in modified duration in Figure 6 (a) is even larger.

**3.2.3 Fire sales.** Large surrender rates translate into large payments that the insurer makes to surrendering policyholders. These negatively affect the insurer's free cash flow. If the free cash flow drops negative, the insurer is forced to sell assets - possible at a fire sale discount. Figure 6 (c) illustrates the impact of surrender rates on the insurer's free cash flow. In the counterfactual calibration with constant surrender rates, the free cash flow is positive at roughly 3% of the previous year's total assets, implying that the cash flow from asset investments and new insurance premiums is more than sufficient to pay out maturing and surrendering policyholders. In contrast, in our baseline calibration surrender rates increase and depress the free cash flow into negative territory from $t = 3$ onward. Each year $t \geq 3$, the insurer is forced to sell roughly 1.5% of its previous year's total assets.

Forced asset sales depress asset prices by roughly 90bps, as Figure 7 shows. This is economically significant. For example, a price impact of 100bps corresponds to roughly 2.5 times the daily volatility of a portfolio of German government bonds with 9.4 years duration.[50] Thus, fire sales due to surrender activity can result in significant downward pressure on financial market prices and thereby transmit to other market participants. Importantly, price amplification becomes economically significant only after roughly 3-4 years of rising interest rates. One reason is that the surrender rate only gradually increases in the first years of an interest rate rise. Moreover, increasing surrender activity reduces the insurer's asset base and premium income, which further reduces the insurer's free cash flow going forward.

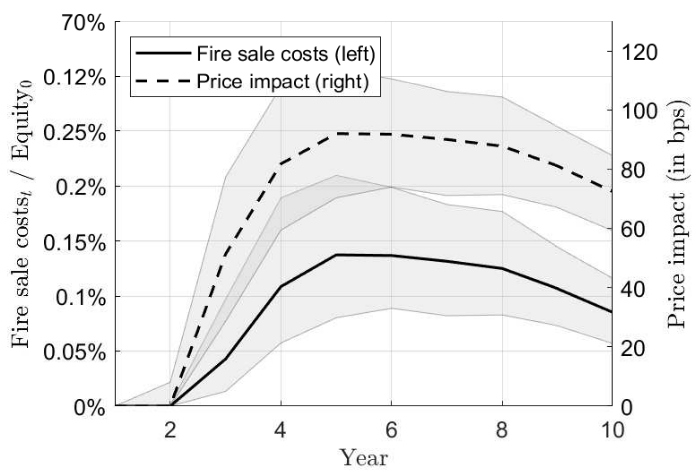



**Figure 7.** Fire sale effects.
The figure depicts fire sale costs relative to the insurer's initial equity capital (left axis) and the relative price discount due to fire sales (right axis) as defined in Section 3.1.5. The figure shows the median and 25th/75th percentile for each year.

While the price impact of fire sales is potentially large, the resulting annual costs for life insurers are relatively small and range from 5bps to up to roughly 15bps as a share of the insurer's initial equity capital (see Figure 7). Consistent with this result, a rough approximation shows that the costs for an insurer that sells 1.5% of its assets with an equity-to-asset ratio of 9% and a 80bps price impact is $0.8 \times \frac{1.5}{9} = 0.13\%$. This example shows that it is mainly the small volume of asset sales

[50] We calculate the daily volatility of a portfolio of German government bonds with 9.4 years duration as follows. We first download daily 10-year German government bond rates from January 1, 1990, to January 1, 2020, from Thomson Reuters Eikon, $\hat{r}_{DE,t}$. Then, the relative price change of a portfolio with a modified duration of 9.4 years between days $t-1$ and $t$ roughly corresponds to $\Delta P_t = (-9.4) \times \frac{\hat{r}_{DE,t} - \hat{r}_{DE,t-1}}{100}$. The sample standard deviation of $\Delta P_t$ is 0.4%.

relative to insurers' equity capitalization that drives the relatively small fire sale costs in Figure 7.

Adding up fire sale costs across years and discounting them with the risk-free rate provides an estimate of the present value of the *cumulative* fire sale costs resulting from a 10-year-long interest rate rise. The present value of fire sale costs is roughly 75bps of insurer's equity capital, which corresponds to 3 bn EUR in our calibration.

We conclude that fire sales caused by life insurance policies' surrender options can result in economically significant price amplification and externalities to other financial institutions, which is due to the substantial size of life insurers on financial markets. However, the resulting costs for life insurers themselves are rather low in the baseline calibration since the volume of asset sales is small relative to their equity capitalization.

### 3.3 Sensitivity: Role of long-term investments and insurer's capitalization

As we argue above, the mechanism through which an interest rate rise triggers fire sales is the slow pass-through from market interest rates to policy returns. This slow pass-through is due to the long duration of the insurer's assets, incentivizing policyholders to surrender their policy. In the following, we provide additional analyses on this mechanism by examining the sensitivity of our results toward the duration of the insurer's assets. For this purpose, we change the duration of fixed income assets (proportionally across asset classes) and re-simulate the model. Additionally, we also vary the insurer's capitalization by adjusting the initial equity capital ratio.

Figure 8 shows that a higher asset duration reduces the insurer's investment return in excess of the risk-free rate - a decline by roughly 5ppt (on average across years) when asset duration increases from 8.4 to 13 years.[51] As a result, surrender incentives increase and cause a rise in the average surrender rate (across years) by roughly 1ppt.

Due to increased surrender activity, the insurer is forced to sell relatively more assets, which causes larger price amplification effects. As we show in Figure 9 (a), the average price impact (across years) increases from roughly 20bps to 110bps when the asset duration increases from 8.4 to 13 years.

While asset duration is hence a crucial determinant for the size of fire sale externalities, we

[51] In EIOPA (2016)'s stress test, participating insurers', mostly life insurers', asset duration ranged from 2.73 (Cyprus) to 12.45 (U.K.) years at the country-average, as of January 2016.

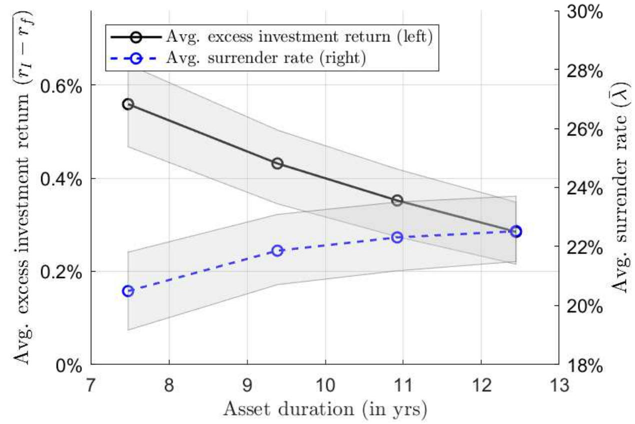
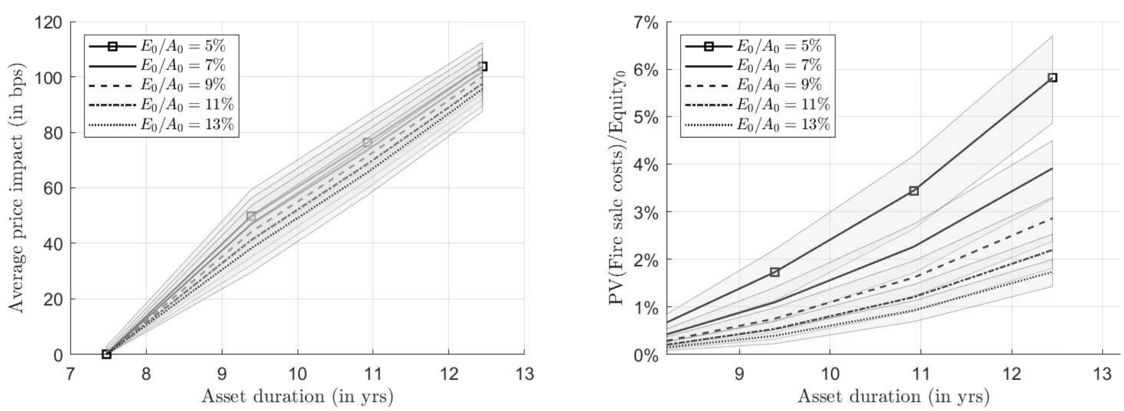



**Figure 8.** Effect of asset duration on investment return and surrender rates.
The figure depicts the average insurer's investment return in excess of the 10-year risk-free rate across years (left axis) and the average surrender rate across years (right axis) at the median and 25th/75th percentiles. We vary the initial asset duration on the x-axis, holding the distribution of relative duration levels across assets constant as in the baseline calibration.




(a) Average price amplification.

(b) Cumulative fire sale costs.

**Figure 9.** Effect of asset duration and initial solvency ratio on fire sale externalities and costs.
Figure (a) depicts the average price impact of fire sales (across years) for different levels of initial asset duration and solvency ratio of the insurer. Figure (b) depicts the present value of cumulative fire sale costs relative to the insurer's equity capital for different levels of initial asset duration and solvency ratio of the insurer. We show the median and 25th/75th percentiles, and vary the initial asset duration on the x-axis, holding the distribution of relative duration levels across assets constant as in the baseline calibration.

find that an insurer's capitalization is largely irrelevant - given a fixed size of the insurance policy portfolio. The reason is that neither the insurer's investment return nor policy returns and surrender rates depend on the insurer's capital ratio (in the model). Thus, the total volume of fire sales is largely independent of the relative capitalization of the insurer.

Resulting from a stronger price impact, a higher asset duration can substantially increase fire sale costs. Our model predicts that an increase in asset duration from 8.4 to 13 years results in an increase in the present value of cumulative fire sale costs from below 1% to 3% for an insurer with an initial equity capital ratio of 9%, as in our baseline calibration. Thus, a long asset duration substantially boosts relative fire sale costs up to economically highly significant levels.

Since the fire sale volume and price impact are largely independent of the insurer's capitalization, total fire sale costs are as well. As a result, more weakly capitalized insurers suffer from larger *relative* fire sale costs, as Figure 9 (b) illustrates. Insurers with an initial capital ratio 5% face cumulative fire sale costs of up to 6% of their initial equity when their assets have a high duration (of 13 years). These results underline the key mechanism by which surrender options in life insurance policies contribute to life insurer fragility and can generate externalities via price amplification: the long-term investment strategy of life insurers exposes them to liquidity risk stemming from policy surrender options, which are relatively more attractive during an interest rate rise. Forced asset sales resulting from policy surrenders can lead to a substantial price amplification on financial markets and losses in insurers' net worth under plausible assumptions.

### 3.4 Robustness: Sharp interest rate rise

We additionally calibrate a sharp and sudden interest rate rise. In the first two years of this environment, interest rates increase by roughly 4.5ppt; in subsequent years, interest rates stabilize. In this case, market interest rates approach policy returns much faster, resulting in an immediate surge in surrender rates to up to 30%. As a result, fire sale costs rise to up to 1.2% p.a. of the insurer's initial equity and fire sales reduce asset prices by up to 200bps. These results highlight that a sudden and severe drop in asset prices can substantially amplify fire sale externalities resulting from surrender options in life insurance policies.

## 4 Empirical predictions and policy implications

Our analysis sheds light on the interaction between market interest rates, surrender options included in life insurance policies, asset sales by life insurers, and asset prices. Thereby, we derive several empirical predictions.

First, we uncover substantial convexity in the interest rate sensitivity of life insurance policies.

In our baseline calibration, the duration of life insurance policies drops by roughly 4 to 5 years due to surrender activity during an interest rate rise, relative to the duration in a counterfactual calibration without price-dependent surrender activity. This convexity lowers the interest rate sensitivity of life insurers' liabilities when interest rates increase. This prediction is consistent with empirical evidence on the interest rate sensitivity of life insurers' equity prices. For example, by comparing U.S. life insurers (that typically supply guarantees and surrender options) to U.K. life insurers (that do typically *not* guarantee surrender values), Hartley et al. (2017) document that U.S. life insurers' equity prices become relatively less interest-rate-sensitive when interest rates increase.

Convexity affects the interest-rate sensitivity of insurers' equity capital ratio, for which a second-order approximation yields

$$\Delta(E/A) = -\frac{A-E}{A} \times \Delta r_f \times \left[\left(D^A - D^L\right) + \frac{\Delta r_f}{2} \times \left(D^A - D^L\right)^2 - \frac{\Delta r_f}{2} \times \left(\frac{\partial D^L}{\partial r_f} - \frac{\partial D^A}{\partial r_f}\right)\right], \tag{11}$$

where $D^L$ and $D^A$ are the modified duration of life insurance policies and life insurers' assets, respectively, $A$ are assets, $E$ is (the market value of) equity capital, and $\Delta r_f$ are changes in the risk-free rate.[52] Under the assumption of negligible asset convexity, $\frac{\partial D^A}{\partial r_f} \approx 0$, matching the duration of assets and life insurance policies ($D^A = D^L$) results in an unhedged position due to convexity, $\frac{\partial D^L}{\partial r_f} < 0$, which then implies that $\Delta(E/A) < 0$, i.e., a short position in interest rates. Instead, it is optimal for life insurers to maintain a negative duration gap ($D^A - D^L < 0$) in order to smooth the interest rate sensitivity of their equity capital ratio.[53] A negative duration gap thus balances the effect of life insurance convexity. This result provides an explanation for why most life insurers worldwide exhibit negative duration gaps (e.g., IMF (2019)).

Second, convexity incentivizes insurers to reduce (increase) the duration of their assets upon an

[52] Note that (modified) duration reflects the sensitivity of price $P$ with respect to yield $r$ and is defined as $D(r) = -P'(r)/P$, which implies that $D'(r) = -\frac{P''(r)P - P'(r)^2}{P^2} = -\frac{P''(r)}{P} + D(r)^2$. Hanson (2014) defines convexity by $(1/2)P''(r)/P = (1/2)(D(r)^2 - D'(r))$. Following his definition, an asset is positively convex if $-D'(r)$ is large, more specifically if $-D'(r) > -D(r)^2$. We take a slightly more narrow definition and call an asset positively convex if $-D'(r) > 0$. Since $D > 0$, $-D'(r) > 0$ implies $-D'(r) > -D(r)^2$. Our definition is motivated by the fact that $D'(r)$ determines whether duration-matching hedges an insurer's equity ratio against interest rate risk, as Equation (11) shows.

[53] Equity capital ratio is a key metric for insurers, e.g., due to capital-based regulation. Our model indeed indicates that asset convexity is small, see Figure 6 (a).

interest rate rise (decline) in order to match the decline in policy duration. A collective re-balancing can induce price pressure on long-term interest rates relative to short-term interest rates, analogous to the mechanism in Hanson (2014) for fixed-rate mortgages. This prediction is consistent with the results in Domanski et al. (2015), who empirically document that German life insurers increase asset duration upon an interest rate decline and that the increased demand for long-term bonds further reduces long-term yields (which is the reverse to our setting, but consistent with the prediction). Ozdagli and Wang (2019) provide additional empirical evidence for a negative correlation between demand for relatively long-term bonds by U.S. life insurers and the level of market interest rates.

Third, our results suggest that surrender options can force life insurers to liquidate a substantial share of their assets when asset prices decline. Under plausible assumptions, we estimate an asset price impact of such asset liquidations of up to 1% and the fire sale costs for insurers of up to 0.15% of their equity capital annually. A longer asset duration can substantially amplify the effect. Thus, our model predicts a positive correlation between surrender activity of policyholders and the volume of asset liquidations, and a negative correlation between surrender activity and the prices of insurers' initial asset investments. The latter effect amplifies a potential price impact from duration re-balancing (as in the second prediction) during an interest rate rise (with increased surrender activity), but (partly) offsets a duration re-balancing-induced price impact during an interest rate *decline* (with reduced surrender activity). Fire sale externalities may be amplified by other liquidity shortages of life insurers during an interest rate rise, such as the obligation to post variation margins for interest rate swaps (De Jong et al. (2020)).[54]

Fire sale externalities arise in our framework because surrender values do not react to (short-term) asset price fluctuations and, therefore, insurers *collectively* face increased surrender activity. Instead, decoupling surrender incentives from asset prices can remove the correlation of surrender activity across insurers and, thereby, reduce correlated asset sales. One possibility to decouple surrender incentives and asset prices is to align surrender values to market prices. If, for example, in our model surrender values were equal to the value of future policy cash flows (discounted at current market rates), surrender incentives would be independent of market interest rates (cf. Equation (6)). Market value adjustments (MVAs), which are common during the first years of U.S.

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

life insurance policies, take one step in that direction by adjusting surrender values to changes in market interest rates (see, e.g., Förstemann (2019)). However, MVAs are not common practice in many European life insurance markets. This observation suggests that it is individually optimal for life insurers not to offer them, e.g., because the liquidity provided by life insurance policies is highly valued by policyholders. This argument is consistent with Gottlieb and Smetters (2016)'s model, in which life insurers price surrender options such that an increase in surrender rates is ex-post profitable for insurers. However, our results highlight that surrender options may generate economically significant externalities to financial markets. To mitigate such externalities, MVAs can be a viable policy tool.

In contrast to MVAs, large surrender penalties are costly for policyholders also when interest rates decline, while there are negligible externalities from collective surrender activity in these times. Similarly, the temporary suspension of surrender payments can mitigate the (short-term) impact of collective surrenders, however at the expense of policyholders that surrender due to idiosyncratic liquidity needs (similarly to a deposit freeze aimed to prevent bank runs).[55] Thus, although policymakers consider surrender suspensions as a valid policy instrument and suggest to use surrender penalties for the purpose of managing life insurers' liquidity risk (e.g., ESRB (2020)), our findings suggest that the use of MVAs is more effective to mitigate externalities from surrender activity.

# 5 Conclusion

Consumers can prematurely withdraw their savings from life insurance policies, i.e., *surrender*, receiving an ex-ante guaranteed surrender (cash) value. Because exercising this option becomes relatively more in-the-money when interest rates increase, yield-oriented policyholders then have larger incentives to surrender and earn the difference between the surrender value and the market value of assets supporting their policies.

In a large panel dataset, we empirically document that surrender options cause *convexity* in the interest rate sensitivity of life insurance policies: when interest rate rise, surrender rates increase.

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

This reduces life insurance policies' duration. Our results strongly suggest the effect of interest rates on surrender activity is due to yield-oriented policyholders.

When policyholders exercise the surrender option, they may force life insurers to sell assets. Collective asset sales can cause fire sale costs to insurers and fire sale externalities to other financial market participants – particularly due to the size and illiquidity of life insurers' asset investments. We present a calibrated model to estimate fire sales. Simulations of our model predict that asset sales forced by increased surrender activity during a plausibly calibrated interest rate rise reduce asset prices by up to 100bps, which corresponds to roughly 2.5 times the daily volatility of German government bonds. We estimate fire sale costs for an average insurer to be up to 15bps of equity capital per year and cumulative fire sale costs over 10 years of 1% of initial equity capital (roughly 3 bln EUR). These effects substantially increase with the duration of life insurers' assets – up to a price impact of 110bps and cumulative fire sale costs of 3% of initial equity for still empirically justified levels of asset duration. Fire sales resulting from withdrawals in life insurance have thus an economically sizable impact on other financial markets as well as on life insurers themselves. We conclude that surrender options embedded in life insurance policies can plausibly amplify shocks in the financial system and contribute to systemic risk.

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

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# Online Appendix

## A Surrender options in the U.S.

In the U.S., the surrender value highly depends on the product type. For individual deferred annuities, the surrender value should at least correspond to 87.5% of the accumulated gross cash value up to the surrender date and additional interest credits less surrender charges (NAIC (2017)). Similar to German life insurance policies, the guaranteed minimum interest rate is determined at policy begin.[56] Therefore, surrendering policyholders receive a minimum guaranteed value which is independent of market developments.

For modified guaranteed annuities (and variable annuities) a cash surrender benefit also exists. However, the surrender value (at least in the first policy years) depends on a market value adjustment (MVA). This can cause both upward and downward changes based on market developments (NAIC (2011)). In general, the MVA compares interest rates at policy begin with rates at the surrender date. If interest rates have increased (decreased) during the active policy period, the effect of the MVA on the surrender value will be negative (positive), i.e., the policyholder will receive relatively less (more).[57]

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

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

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

# B Additional empirical results

**Table 6.** Robustness: U.S. interest rates and surrender rates
Fixed effects regressions of insurers' annual surrender rate on the federal funds rate, 10Y U.S. and German government bond yields from 1996 to 2019. Macro controls: 1-year lagged inflation, GDP growth, investment growth, banking crises in Germany. Sources: BaFin (insurer-level surrender rate), German Bundesbank (interest rate), Federal Reserve Bank Reports database in WRDS (federal funds rate), St. Louis FRED (U.S. interest rate), BIS (inflation), OECD (GDP, investment growth), Laeven and Valencia (2018) (crisis indicator). Standard errors clustered at year and firm level. ***, **, * indicate significance at the 1%, 5% and 10% levels respectively. P-values are in parentheses.

| | (1) | (2) | (3) |
|---|---|---|---|
| Dependent variable: | | Surrender rate | |
| Interest rate$_t$ | | 0.361*** | 0.383*** |
| | | (0.000) | (0.000) |
| Federal funds rate$_t$ | 0.239*** | -0.006 | |
| | (0.000) | (0.859) | |
| U.S. interest rate$_t$ | | | -0.039 |
| | | | (0.661) |
| Insurer FE | Yes | Yes | Yes |
| Macro controls | Yes | Yes | Yes |
| No. of obs. | 2,263 | 2,263 | 2,263 |
| No. of insurers | 163 | 163 | 163 |
| $R^2$ | 0.734 | 0.749 | 0.749 |
| $R^2$ within | 0.176 | 0.224 | 0.224 |

# C Model and calibration details

## C.1 Calibration of surrender decisions

We calibrate the model for policyholders' surrender decision described in Section 3.1.2 exploiting the data on German life insurers' surrender rates described in Section 2. Model inception, $t = 0$, corresponds to year-end 2015. We calibrate the surrender rate in the model implied for the beginning of the first period, corresponding to 2016. Since empirical data for early surrender rates is available only until 2015, we use the distribution of surrender rates in 2015. In Figure 10, we show that the distribution of the total insurer-level surrender rate is similar in 2015 and 2016, as German interest rates were very stable in these years.

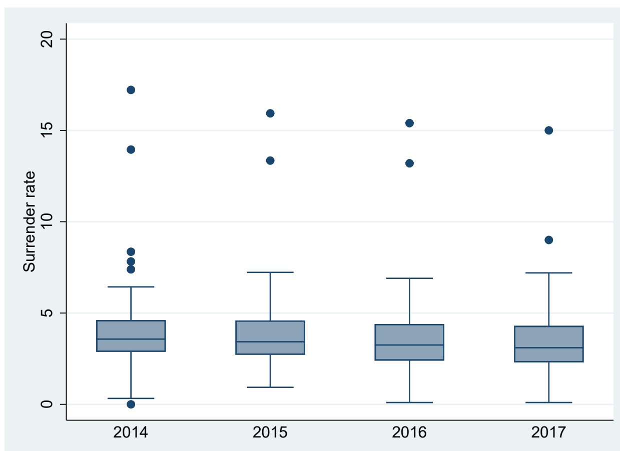



**Figure 10.** Distribution of surrender rates across German life insurers.

We then calibrate the model's parameters $\beta_0, \beta_1$, and $\beta_2$ as follows, trying to make as few additional assumptions about the distribution of surrender rates as possible:

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

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

6.3%,

$$\lambda_{h+1}^{h} = 1 - \Phi\left(\beta_0 + \beta_1 \log\left(\vartheta^{-1}\left(\frac{1+\tilde{r}_h^h}{1+r_f(h)}\right)^{40}\right) + \beta_2 \log(2)\right) \stackrel{!}{=} 0.063. \tag{12}$$

(3) To calibrate the sensitivity toward policy returns, the surrender rate of policies in their first year with a policy return that coincides with the 10-year sovereign bond yield (1.225%) equals the *early* surrender rate of the median German life insurer in 2015 (weighted by contract portfolio size) among those insurers with the 10% smallest absolute difference between investment return and risk-free rate, which is 24.6%,

$$\lambda_{h+1}^{h} = 1 - \Phi\left(\beta_0 + \beta_1 \log\left(\vartheta^{-1}\left(\frac{1+\tilde{r}_h^h}{1+r_f(h)}\right)^{40}\right) + \beta_2 \log(2)\right) \stackrel{!}{=} 0.246. \tag{13}$$

Here, the assumption is that an insurer's investment return proxies for its policies' returns.[58]

The resulting calibration is $(\beta_0, \beta_1, \beta_2) = (0.5074, 1.3847, 0.2088)$.

## C.2 Calibration of initial policy portfolio

To calibrate the cash value of policy cohorts at model initiation we use:

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

[58]Note that the investment return is a good proxy for the policy return particularly for policies sold in 2015 since their guarantee was below insurers' investment returns. For example, the average (policy portfolio-weighted) investment return was 2.5% in 2015 (according to BaFin) and the average profit participation rate was 3.3% (according to Assekurata Cologne (2016)), while the guaranteed return for new policies was 1.25%.

Denote by $N^h$ the number of new policies in year $t = h$ and by $\tilde{\lambda}^t$ the average surrender rate (reported by BaFin) in year $t$ in Germany (where $t = 0$ corresponds to 2015). Due to the absence of more granular, we make the following assumptions: (1) within each cohort $h$ each policy pays a 1 EUR premium each year if not surrendered or matured, (2) each policy has a 30-year duration at inception, (3) each existing policy's surrender rate in year $t$ can be approximated by the average surrender rate $\tilde{\lambda}^t$. However, starting to accumulate policies in 1976, these assumptions must not necessarily arrive at the representative policy policy in 2015. Instead, policies in practice may deviate from these assumption due to the presence of one-time premia, heterogeneous surrender rates, and changes in insurance supply (e.g., due to insurer failures).

To evaluate the representativeness of the implied 2015-policy portfolio, we use two key portfolio characteristics: the average guaranteed return per policy and the modified duration.[59] Assekurata Cologne (2016) reports an average guaranteed return of 2.97% for German life insurers in 2015 and the German Insurance Association (2015) reports a modified duration of roughly 14.1 years for the median German life insurer. Following the assumption above, our initial portfolio would exhibit a much lower modified duration (10.7 years). Thus, early policies have a two large weight in the portfolio. To offset this bias, we modify cohort sizes by a multiplicative trend, using

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

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

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

[59] Consistent with EIOPA (2016), we calculate a policy's modified duration as

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

where

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

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

our model.

## C.3 Calibration of the insurer's investment portfolio

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

The weights within sub-portfolios are based on Berdin et al. (2017) and EIOPA (2014) and reported in Table 7. We include a large home bias toward German government bonds, which, however, has small impact on our results. Due to the absence of more granular data, we calibrate real estate and stock weights in order to yield a plausible home bias of 60% for German real estate and stocks, and distribute the remaining weights equally.

| **Entire Investment Portfolio** | **Weight** | **Duration** |
|---|---|---|
| Sovereigns $w_{\text{sov}}$ | 55.3% | 10.4 |
| Corporate $w_{\text{corp}}$ | 34.1% | 7.5 |
| Stocks $w_{\text{stocks}}$ | 6.7% | - |
| Real Estate $w_{\text{real estate}}$ | 3.9% | - |
| **Sovereign Bond Portfolio** | **Weight** | **Modified Duration** |
| German Sovereigns/All Sovereigns $w_{\text{DE}}$ | 90.4% | 10.45 |
| French Sovereigns/All Sovereigns $w_{\text{FR}}$ | 2.4% | 10.12 |
| Dutch Sovereigns/All Sovereigns $w_{\text{NL}}$ | 2.4% | 10.45 |
| Italian Sovereigns/All Sovereigns $w_{\text{IT}}$ | 2.4% | 8.03 |
| Spanish Sovereigns/All Sovereigns $w_{\text{ES}}$ | 2.4% | 10.45 |
| **Corporate Bond Portfolio** | **Weight** | **Duration** |
| AAA/All Corporates $w_{\text{AAA}}$ | 23.6% | 7.36 |
| AA/All Corporates $w_{\text{AA}}$ | 16.85% | 8.08 |
| A/All Corporates $w_{\text{A}}$ | 33.71% | 7.65 |
| BBB/All Corporates $w_{\text{BBB}}$ | 25.84% | 7.22 |
| **Stocks and Real Estate Portfolios** | **Weight** | |
| German/Portfolio $w_{\text{s/re DE}}$ | 60% | - |
| French/Portfolio $w_{\text{s/re FR}}$ | 10% | - |
| Dutch/Portfolio $w_{\text{s/re NL}}$ | 10% | - |
| Italian/Portfolio $w_{\text{s/re IT}}$ | 10% | - |
| Spanish/Portfolio $w_{\text{s/re ES}}$ | 10% | - |

**Table 7.** Investment portfolio allocation.
The table depicts the weights and average modified duration of each asset class in the insurer's investment portfolio.

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 reports of EIOPA (2016, Table 6) (9.6 years for 2015), EIOPA (2014) (8.2 years for 2013). EIOPA (2014) reports an average duration of 9.5 years for sovereigns and 6.9 years for corporate bonds for 2013.

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

### C.4 Calibration of the short-rate model

The stochastic differential equation (8) can be solved, which yields (cf. Brigo and Mercurio (2006))

$$r(t) = r_0 e^{-\alpha_r t} + \alpha_r \int_0^t e^{-\alpha_r (t-u)} \theta_r(u)\, du + \sigma_r \int_0^t e^{-\alpha_r (t-u)}\, dW_r(u). \tag{14}$$

Thus, the short-rate is normally distributed, i.e., $r(t) \sim \mathcal{N}(\mu_t, \sigma_t^2)$, with parameters

$$\mu_t = \mathbb{E}[r(t)] = r(0) e^{-\alpha_r t} + \alpha_r \int_0^t \theta_r(u) e^{-\alpha_r (t-u)}\, du \tag{15}$$

$$\sigma_t^2 = \text{var}(r(t)) = \frac{\sigma_r^2}{2\alpha_r} \left(1 - e^{-2\alpha_r t}\right). \tag{16}$$

The price $P(t, \tau)$ of a zero-coupon bond at time $t$ with time to maturity $\tau$ is given by (cf. Hull and White (1990) and Brigo and Mercurio (2006))

$$P(t, t+\tau) = A(t, t+\tau) e^{-r(t)\, B(\tau)}, \tag{17}$$

where

$$B(\tau) = \frac{1 - e^{-\alpha_r \tau}}{\alpha_r},$$
$$A(t, t+\tau) = \exp\left(\frac{\sigma_r^2}{2\alpha_r^2}(\tau - B(\tau)) - \frac{\sigma_r^2}{4\alpha_r} B^2(\tau) - \alpha_r \int_t^{t+\tau} \theta_r(u) B(t+\tau-u)\, du\right).$$

Hence, the continuously compounded spot rate at time $t$ for time to maturity $\tau$ is given by

$$\hat{r}_{f,\tau}(t) = -\frac{1}{\tau} \log P(t, t+\tau) = \frac{B(\tau) r(t) - \log A(t, t+\tau)}{\tau} \tag{18}$$

and the equivalent annually-compounded spot rate is given by

$$r_{f,\tau}(t) = e^{\hat{r}_{f,\tau}(t)} - 1 = \left(\frac{e^{B(\tau)\, r(t)}}{A(t, t+\tau)}\right)^{1/\tau} - 1. \tag{19}$$

To yield rising interest rates, we choose the mean reversion level to be

$$\theta_r(t) = \gamma + (\beta - \gamma)\left(1 - \frac{1}{1 + e^{-bt}}\right). \tag{20}$$

We select parameters for the short rate model in order to imply gradually increasing interest rates (by choosing $b = 5$) and sharply increasing interest rates (by choosing $b = 10$). Thereupon, we calibrate the initial short-rate $r(0)$, speed of mean reversion $\alpha_r$, volatility $\sigma_r$, and mean reversion parameters $\gamma$, $\beta$, and $b$ with historical data in order to match (a) the short rate volatility at a given point in time $\bar{t}$, $\text{var}(r(\bar{t}))$, with the daily volatility of the Euro OverNight Index Average (EONIA) from January 1999 to March 2016[60], (b) the yield of 10, 15, and 20-year German sovereign bonds in 2015 as a proxy for the term structure of risk-free rates at $t = 0$[61], and (c) a predetermined target level for the risk-free interest rate $r_{f,10}(t)$ that determines the interest rate rise severity.[62] For this purpose, we minimize the weighted sum of squared deviations between (a) EONIA volatility and

[60] 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*. The descriptive statistics are: mean=1.96%, sd=1.58%, (p25,p5,p75)=(0.34%, 2.07%, 3.3%). We set $\bar{t} = 5$ and calculate the EONIA volatility based on the deviation of EONIA from its weighted exponential moving average.

[61] Initial long-term risk-free rates are $r_{f,10}(0) = 0.52\%$, $r_{f,15} = 0.91\%$ and $r_{f,20}(0) = 1.12\%$. German sovereign bond yields are retrieved from the *German Bundesbank*.

[62] We choose $r_{f,10,10} = 3\%$ for gradually increasing and $r_{f,10}(10) = 3.5\%$ for sharply increasing rates.

short rate model-implied volatility, (b) long-term yields, and (c) target risk-free rate. The results are reported in Table 3.1.4.

| Parameter \ Environment | Gradual | Sharp |
|---|---|---|
| $r(0)$ | -0.77% | -71.2% |
| $\alpha_r$ | 0.0462 | 2 |
| $\sigma_r$ | 0.32% | 1.3% |
| $\beta$ | -0.7021 | 0.6367 |
| $\gamma$ | 0.0705 | 0.0346 |
| $b$ | 10 | 3 |

**Table 8.** Calibration of the short-rate model.
$r(0)$ is the initial short rate, $\alpha_r$ the speed of mean reversion, $\sigma_r$ the volatility, $\beta$ and $\gamma$ the initial and long-term level of mean reversion, respectively, and $b$ a skewness parameter. We calibrate gradually and sharply increasing interest rates, respectively.

## C.5 Calibration of financial market securities' processes

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

$$s^j(t) = \max\left(k^j(\bar{s}^j - s^j(t))dt + \sigma^j dW^j(t)\right)^+ \tag{21}$$

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

We calibrate bond spreads and stock and real estate returns based on monthly data from January 1999 to December 2007. Corporate bond yields are from the effective yield of the AAA/AA/A/BBB-subset of the ICE BofAML US Corporate Master Index (obtained from *FRED St. Louis*), which tracks the performance of U.S. dollar denominated investment grade rated corporate debt publicly issued in the U.S. domestic market. To take different inflation (expectations) between the EU and U.S. into account, we calculate bond spreads with respect to the yield of U.S. treasuries with a maturity of 10 years (obtained from *FRED St. Louis*).[63] Sovereign bond spreads are calibrated based on the spread relative to German bond yields from January 1999 to December 2007 (obtained from *Bloomberg*), averaged across maturities from 1 to 20 years.

[63] Results are similar if we take German sovereign bond yields instead.

Table 9 describes the sample of bond spreads. Note that we retrieve bond yields (and spreads) for maturities 1 to 20 years for each sovereign bond, while corporate bond spreads are calculated by comparing the effective yield of the ICE BofAML US Corporate Index to the 10-year yield. Since we assume the same spread for each maturity, we calibrate the spread process

$$s^j(t) = k^j(\bar{s}^j - s^j(t))dt + \sigma^j dW^j(t) \tag{22}$$

for the average spread across maturities in the case of sovereigns. Parameter estimates are based on Maximum-Likelihood and reported in Table 9. We do not allow bond yields to fall below risk-free rates and, thus, truncate them in the simulation such that $s^j(t) = \max\left(0, k^j(\bar{s}^j - s^j(t))dt + \sigma^j dW^j(t)\right)$.

| Name | # Observations | Mean | Sd | p25 | p75 | $\bar{s}$ | $k$ | $\sigma$ |
|---|---|---|---|---|---|---|---|---|
| Sovereign (French) | 2160 | 0.0001 | 0.0019 | -0.0013 | 0.0014 | 0.0001 | 14.79 | 0.0095 |
| Sovereign (Dutch) | 2160 | -0.0008 | 0.0024 | -0.0024 | 0.0009 | -0.0009 | 19.5 | 0.011 |
| Sovereign (Italian) | 2160 | 0.0005 | 0.0024 | -0.001 | 0.0023 | 0.0005 | 12.09 | 0.0094 |
| Sovereign (Spanish) | 2160 | -0.0006 | 0.0026 | -0.0022 | 0.0012 | -0.0007 | 11.75 | 0.0097 |
| Corporate (AAA) | 108 | 0.009186 | 0.0078 | 0.0015 | 0.0166 | 0.0047 | 0.3407 | 0.0059 |
| Corporate (AA) | 108 | 0.008801 | 0.0098 | -0.00089 | 0.0169 | 0.0046 | 0.2517 | 0.0061 |
| Corporate (A) | 108 | 0.01293 | 0.0083 | 0.0062 | 0.01935 | 0.0099 | 0.312 | 0.0058 |
| Corporate (BBB) | 108 | 0.02042 | 0.0069 | 0.01695 | 0.0251 | 0.0185 | 0.5571 | 0.0068 |

**Table 9.** Descriptive statistics and calibration for bond spreads.
The table reports descriptive statistics (number of observations, mean, standard deviation, 25% and 75% percentiles) and Maximum-Likelihood estimators for the long-term mean ($\bar{s}$), speed of mean reversion ($k$), and volatility ($\sigma$) of the Ornstein-Uhlenbeck process $s^j(t) = k^j(\bar{s}^j - s^j(t))dt + \sigma^j dW^j(t)$ for monthly spreads between (a) sovereign bond yields and German sovereign bonds, and (b) corporate bond yields and the 10Y U.S. treasury bond yield from January 1999 to December 2007. Sovereign bond yields 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 yields. *Source: Authors' calculations, Bloomberg (sovereigns), FRED St. Louis (corporates).*

Stocks and real-estate investments follow Geometric Brownian Motions (GBMs) that are calibrated to the main (market capitalization-weighted) national stock indices DAX (Germany), CAC 40 (France), FTSE-MIB (Netherlands), AEX (Italy), IBEX 35 (Spain), and real estate REIT indices (all obtained from *Bloomberg*). Table 10 reports the descriptive statistics for monthly log-returns. We calibrate the GBM drift and volatility with Maximum-Likelihood estimates for monthly log-returns, that are also reported in Table 10.

Finally, we correlate all stochastic processes via a Cholesky decomposition of their diffusion terms. Table 11 reports the correlation coefficients based on monthly residuals after fitting bond

| Name | # Observations | Mean | Sd | p25 | p75 | GBM Drift | GBM Volatility |
|---|---|---|---|---|---|---|---|
| Stocks (German) | 108 | 0.004196 | 0.06768 | -0.02947 | 0.0423 | 0.07784 | 0.2345 |
| Stocks (French) | 108 | 0.003365 | 0.05175 | -0.02903 | 0.03081 | 0.05645 | 0.1793 |
| Stocks (Dutch) | 108 | -0.0005451 | 0.05705 | -0.02173 | 0.03405 | 0.01298 | 0.1976 |
| Stocks (Italian) | 108 | 0.000884 | 0.05294 | -0.02639 | 0.03213 | 0.02742 | 0.1834 |
| Stocks (Spanish) | 108 | 0.004364 | 0.05379 | -0.02372 | 0.0332 | 0.06973 | 0.1863 |
| Real Estate (German) | 108 | 0.003055 | 0.07021 | -0.02721 | 0.03902 | 0.06624 | 0.2432 |
| Real Estate (French) | 108 | 0.01126 | 0.04268 | -0.006311 | 0.03777 | 0.146 | 0.1478 |
| Real Estate (Dutch) | 108 | 0.006153 | 0.03848 | -0.01544 | 0.03137 | 0.08272 | 0.1333 |
| Real Estate (Italian) | 108 | 0.01018 | 0.06894 | -0.01879 | 0.04678 | 0.1507 | 0.2388 |
| Real Estate (Spanish) | 108 | 0.008379 | 0.06365 | -0.02957 | 0.05599 | 0.1249 | 0.2205 |

**Table 10.** Descriptive statistics and calibration for stocks and real estate.
The table reports descriptive statistics (number of observations, mean, standard deviation, 25% and 75% percentiles) and Maximum-Likelihood estimators for Geometric Brownian Motions for monthly stock and real estate log-returns from January 1999 to December 2007. Stock returns are based on national stock indices (DAX, CAC 40, FTSE-MIB, AEX, and IBEX 35 for Germany, France, Netherlands, Italy, and Spain, respectively), and real estate returns are based on national REIT indices. *Source: Authors' calculations, Bloomberg.*

spreads, stock and real estate returns.[64]

[64] Since our short-rate model is not designed to fit with short rates between 1999 to 2007, we use residuals from fitting EONIA to an ordinary Ornstein-Uhlenbeck process during this period.

| | Short rate | SP (FR) | SP (NL) | SP (IT) | SP (ES) | SP (AAA) | SP (AA) | SP (A) | SP (BBB) | ST (DE) | ST (FR) | ST (NL) | ST (IT) | ST (ES) | RE (DE) | RE (FR) | RE (NL) | RE (IT) | RE (ES) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Short rate | 1 | 0.005 | 0.107 | 0.105 | 0.056 | 0.009 | 0.003 | -0.036 | 0.003 | 0.138 | 0.234 | 0.205 | 0.222 | 0.109 | 0.036 | 0.133 | 0.014 | -0.065 | -0.002 |
| SP (FR) | 0.005 | 1 | 0.935 | 0.92 | 0.925 | -0.163 | -0.138 | -0.134 | 0.001 | 0.014 | -0.038 | 0.095 | 0.051 | -0.04 | -0.014 | -0.066 | -0.033 | 0.001 | -0.031 |
| SP (NL) | 0.107 | 0.935 | 1 | 0.956 | 0.949 | -0.19 | -0.172 | -0.158 | 0.016 | 0.032 | -0.022 | 0.119 | 0.051 | -0.036 | 0.039 | -0.021 | 0.005 | 0.01 | 0.038 |
| SP (IT) | 0.105 | 0.92 | 0.956 | 1 | 0.974 | -0.233 | -0.195 | -0.175 | -0.01 | 0.032 | -0.027 | 0.122 | 0.031 | -0.07 | 0.008 | -0.086 | -0.075 | -0.029 | -0.068 |
| SP (ES) | 0.056 | 0.925 | 0.949 | 0.974 | 1 | -0.198 | -0.164 | -0.153 | 0.024 | 0.026 | -0.026 | 0.105 | 0.018 | -0.085 | 0.016 | -0.091 | -0.084 | 0.004 | -0.045 |
| SP (AAA) | 0.009 | -0.163 | -0.19 | -0.233 | -0.198 | 1 | 0.946 | 0.909 | 0.723 | 0.181 | 0.197 | 0.155 | 0.112 | 0.119 | 0.117 | 0.107 | 0.068 | 0.198 | 0.124 |
| SP (AA) | 0.003 | -0.138 | -0.172 | -0.195 | -0.164 | 0.946 | 1 | 0.951 | 0.758 | 0.182 | 0.197 | 0.148 | 0.107 | 0.106 | 0.119 | 0.058 | 0.05 | 0.192 | 0.079 |
| SP (A) | -0.036 | -0.134 | -0.158 | -0.175 | -0.153 | 0.909 | 0.951 | 1 | 0.849 | 0.069 | 0.081 | 0.055 | 0.022 | 0.027 | 0.03 | -0.023 | -0.024 | 0.168 | 0.023 |
| SP (BBB) | 0.003 | 0.001 | 0.016 | -0.01 | 0.024 | 0.723 | 0.758 | 0.849 | 1 | -0.042 | -0.052 | -0.049 | -0.088 | -0.103 | -0.129 | -0.138 | -0.11 | 0.06 | -0.051 |
| ST (DE) | 0.138 | 0.014 | 0.032 | 0.032 | 0.026 | 0.181 | 0.182 | 0.069 | -0.042 | 1 | 0.937 | 0.912 | 0.823 | 0.8 | 0.433 | 0.257 | 0.397 | 0.441 | 0.191 |
| ST (FR) | 0.234 | -0.038 | -0.022 | -0.027 | -0.026 | 0.197 | 0.197 | 0.081 | -0.052 | 0.937 | 1 | 0.912 | 0.847 | 0.801 | 0.493 | 0.301 | 0.395 | 0.474 | 0.244 |
| ST (NL) | 0.205 | 0.095 | 0.119 | 0.122 | 0.105 | 0.155 | 0.148 | 0.055 | -0.049 | 0.912 | 0.912 | 1 | 0.815 | 0.776 | 0.495 | 0.308 | 0.417 | 0.432 | 0.263 |
| ST (IT) | 0.222 | 0.051 | 0.051 | 0.031 | 0.018 | 0.112 | 0.107 | 0.022 | -0.088 | 0.823 | 0.847 | 0.815 | 1 | 0.769 | 0.366 | 0.275 | 0.435 | 0.504 | 0.184 |
| ST (ES) | 0.109 | -0.04 | -0.036 | -0.07 | -0.085 | 0.119 | 0.106 | 0.027 | -0.103 | 0.8 | 0.801 | 0.776 | 0.769 | 1 | 0.408 | 0.331 | 0.417 | 0.433 | 0.332 |
| RE (DE) | 0.036 | -0.014 | 0.039 | 0.008 | 0.016 | 0.117 | 0.119 | 0.03 | -0.129 | 0.433 | 0.493 | 0.495 | 0.366 | 0.408 | 1 | 0.475 | 0.42 | 0.516 | 0.357 |
| RE (FR) | 0.133 | -0.066 | -0.021 | -0.086 | -0.091 | 0.107 | 0.058 | -0.023 | -0.138 | 0.257 | 0.301 | 0.308 | 0.275 | 0.331 | 0.475 | 1 | 0.677 | 0.449 | 0.527 |
| RE (NL) | 0.014 | -0.033 | 0.005 | -0.075 | -0.084 | 0.068 | 0.05 | -0.024 | -0.11 | 0.397 | 0.395 | 0.417 | 0.435 | 0.417 | 0.42 | 0.677 | 1 | 0.465 | 0.395 |
| RE (IT) | -0.065 | 0.001 | 0.01 | -0.029 | 0.004 | 0.198 | 0.192 | 0.168 | 0.06 | 0.441 | 0.474 | 0.432 | 0.504 | 0.433 | 0.516 | 0.449 | 0.465 | 1 | 0.326 |
| RE (ES) | -0.002 | -0.031 | 0.038 | -0.068 | -0.045 | 0.124 | 0.079 | 0.023 | -0.051 | 0.191 | 0.244 | 0.263 | 0.184 | 0.332 | 0.357 | 0.527 | 0.395 | 0.326 | 1 |

**Table 11.** Correlation matrix for financial market processes.
The table reports the correlation coefficients for increments of standard Brownian motions that drive the short-rate (represented by EONIA), sovereign bond spreads (SP) for France (FR), Netherlands (NL), Italy (IT), Spain (ES), corporate bond spreads (SP) for AAA, AA, A, and BBB-rated bonds, stocks (ST) and real estate (RE) returns. The correlation coefficients are calculated from monthly residuals from January 1999 to December 2007 after fitting the short rate and spread evolution to Ornstein-Uhlenbeck processes, and stocks and real estate returns to Geometric Brownian Motions, respectively. *Source: Authors' calculations, ECB Statistical Data Warehouse (EONIA), Bloomberg (sovereigns, stocks, real estate), FRED St. Louis (corporates).*

# D Sharp interest rate rise

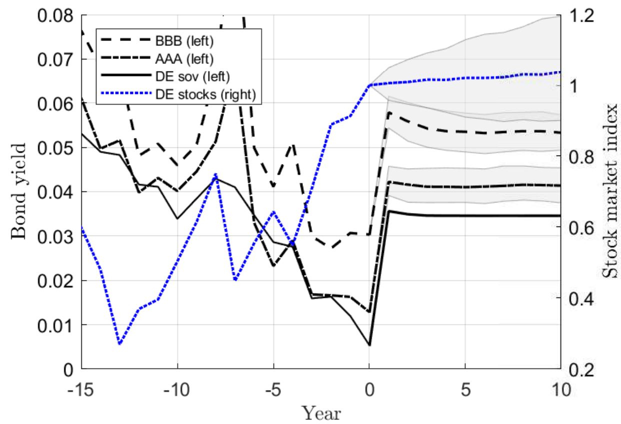
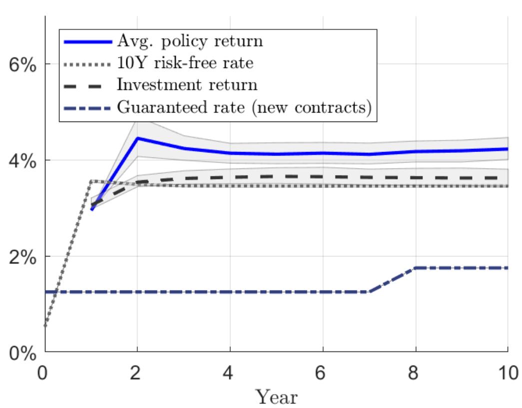
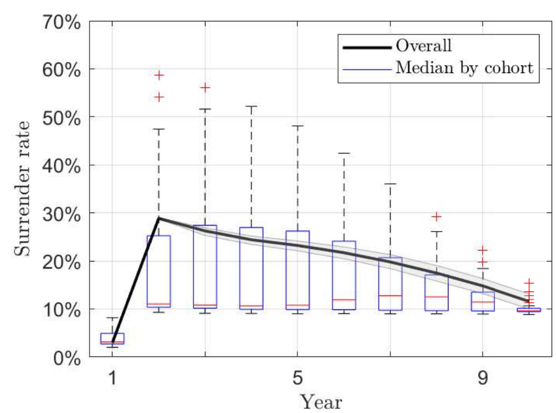



**Figure 11.** Sensitivity analysis with sharp interest rate rise: Financial market dynamics: historical and simulated.

The figure depicts the median and 25th / 75th percentiles of 10-year simulated (a) German government bond, (b) AAA, and (c) BBB bond yields, and (d) German 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. Thereby, AAA and BBB yields are defined as the sum of 10-year German government bond yield and the spread of the AAA- and BBB-subset of the ICE BofAML US Corporate Master Index relative to 10-year U.S. treasury rates (obtained from *FRED St. Louis*).




(a) Interest rates, investment and policy return.




(b) Surrender rates.

**Figure 12.** Sensitivity analysis with sharp interest rate rise: Interest rates, policy returns, and surrender rates.

Figure (a) depicts the market interest rates, the guaranteed return for new policies, the insurer's investment return, and policy returns in each year (median and 25th / 75th percentiles). Figure (b) depicts the share of surrendered policies in each year (median and 25th / 75th percentiles; straight lines) and the distribution of each cohort's median surrender rate across cohorts (boxplots).

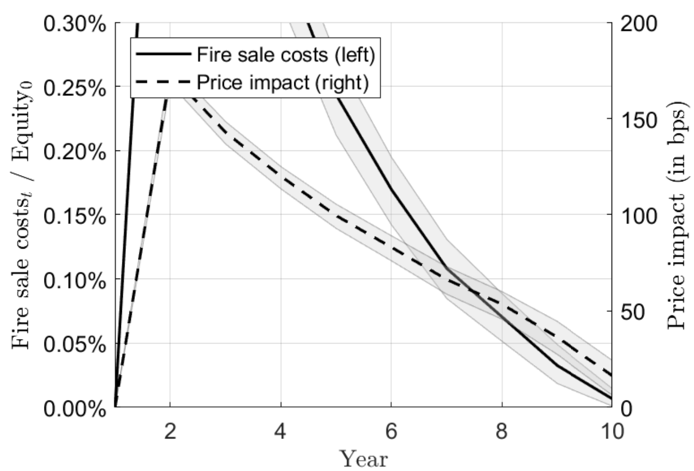



**Figure 13.** Sensitivity analysis with sharp interest rate rise: Fire sale effects.

The figure depicts fire sale costs relative to the insurer's initial equity capital (left axis) and the relative price discount due to fire sales (right axis) as defined in Section 3.1.5. The figure shows the median and 25th/75th percentile for each year.