Banks and non-banks stressed: liquidity shocks and the mitigating role of insurance companies

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Abstract

This paper documents the extension of the system-wide stress testing framework of the ECB with the insurance sector for a more thorough assessment of risks to financial stability. The special nature of insurers is captured by the modelling of the liability side and its loss absorbing capacity of technical provisions as the main novel feature of the model. Leveraging on highly granular data and information on bilateral exposures, we assess the impact of liquidity and solvency shocks and demonstrate how a combined endogenous reactions of banks, investment funds and insurance companies can further amplify losses in the financial system. The chosen hypothetical scenario and subsequent simulation results show that insurers' ability to transfer losses to policyholders reduces losses for the entire financial sector. Furthermore, beyond a certain threshold, insurance companies play a crucial role in mitigating both direct and indirect contagion.

Keywords: Financial stability, stress test, interconnectedness, insurance companies, fire sales, contagion

JEL: D85, G01, G21, G23, L14

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Non-technical summary

The Great Financial Crisis had a significant impact on the financial system in the euro area, with non-banking financial institutions (NBFIs) such as investment funds, insurers and market-based credit becoming increasingly important. These developments have led to NBFIs gaining a relevant position in the transmission of shocks from the real economy to the financial system. As a result, regulators concluded that there is a need for a more holistic risk assessment that takes into account the complex interactions among different financial institutions, i.e. a stress testing model that goes beyond banks is required for a more refined analysis of the financial system, and vice versa.

In this paper, the two-sector stress testing framework of the European Central Bank (Sydow et al., 2024) is extended to cover, in addition to a granular network of banks and investment funds, also the insurance sector. The main methodological improvement compared to similar approaches is that the model better reflects the nature of the life insurance business, by including an estimation of the loss absorbing capacity of technical provisions. This specific component, within the limitation of the model and the data used for the calibration, allows to include in the estimation of the impacts of the shocks, the ability offered by life policies based on profit participation to transfer part of the losses on the asset portfolios backing these contracts to policyholders. Firm-level information is used to estimate the loss-absorbing capacity for market valuation losses from bonds and equities held by insurers. Furthermore, this loss transmission is also calculated for investment fund shares based on granular fund holdings data and insurers' fund share information.

As a first application of the three-sector model for illustrative purposes, we consider a Network for Greening the Financial System (NGFS) 'hot house world' scenario featuring an increase in credit risk losses and a market shock with asset price devaluations. However, more standard macro-financial shock scenarios, such as the ones developed by the ESRB/ECB for the stress testing exercises conducted by the European Supervisory Authorities, could as well be analysed with this model. A final innovation is the definition of an add-on scenario of liquidity shocks applied to all sectors in the form of interbank funding withdrawals, fund redemptions and insurance surrenders.

Results show sensitivities of current balance sheets of financial sectors. We show that the interconnected financial system of banks, funds, and insurers amplifies initial macro-financial shocks. Mild shocks are applied to the system, but exogenous insurance policy surrenders drive second-round losses. The authors discover sizable second-round amplification effects that are noteworthy in all three sectors. Portfolio overlaps and cross-holdings of fund shares and securities are the main sources of second-round losses and insurers are the major drivers of investment fund redemptions due to their large fund share holdings.

Additionally, the ability of insurance undertakings to partly transfer the losses to policyholders allowed by profit participation features embedded in specific life portfolios, proves its effectiveness in absorbing part of the shocks and eventually reducing their losses and those of the entire financial system. Sensitivity analysis shows that scaling up market shocks and insurance surrenders increases loss reduction for the whole financial system, especially when insurance undertakings' defaults are prevented by the loss absorbing capacity.

We conclude that our findings advocate for the use of system-wide stress testing models, which consider both banks and non-banks, and highlight the need to model the insurers' liability side for a more realistic stress test result. The current model can be expanded to investigate the impact of changes in monetary policy, and given the comprehensive set of mechanisms included, it can also be applied to investigate the effect of several macroprudential measures like additional capital buffer requirements or fund-level redemption restrictions.

1 Introduction

In the aftermath of the Great Financial Crisis in 2007-2009, the euro area financial structure has undergone a significant evolution, resulting in non-banking financial intermediation and market-based credit gaining a prominent position in financing the real economy (ECB, 2021). Non-bank financial institutions (NBFIs) have strengthened their role in financial markets: over the past decade total assets held by euro area NBFIs have in fact roughly doubled. As at end-2021 NBFIs collectively held financial assetsamounting to about €31.7 trillion, which represented 37.3% of the entire financial sector (ECB, 2022). Moreover, the amount of debt securities issued by non-financial corporations (NFCs) in the euro area has also doubled in the last decade, and investment funds, insurance corporations, and pension funds currently hold more than 40% of outstanding euro area NFC market debt jointly (ECB, 2022). Finally, in the last few years equity holdings of investment funds saw a significant growth, followed by equity holdings of insurance companies, and pension funds also buying investment fund shares (ECB, 2022).

As a result of these developments, NBFIs have gained a relevant position in the transmission of shocks from the real economy to the financial system; it is NBFIs' new position that mandates a more holistic risk assessment (Girardi et al., 2021). Therefore, for a comprehensive assessment of systemic risk, a stress testing model with a perspective that extends beyond banks is required for a more refined analysis of the financial system and the complex interactions among different financial intermediaries occurring in it. Thanks to this comprehensive approach, policy institutions are in a better position to more realistically and quantitatively analyse the impacts of their actions and decisions.

In an effort to fully comprehend macro-financial risks and system-wide amplification effects, the aim of the present work is to analyse the short-term dynamic reaction of a granular network of banks, investment funds and insurers conditional on macro-financial shock scenarios and to present the progress made on the development of the system-wide stress testing model by the ECB (Sydow et al., 2024; Budnik et al., 2024). Our model uses an operational framework based on granular, firm-level data to analyse several financial sectors, incorporating interconnectedness effects within a wider definition of the financial system that goes beyond the banking and investment fund sectors.

We intend to contribute with this paper to a limited but growing body of literature. Few works in the macroprudential stress testing literature model multiple financial sectors with real-world institutional features jointly. Calimani, Hałaj, and Żochowski (2019) investigate contagion using an agent-based framework with two different agents, traditional banks and asset managers, and a model-driven fire-sale mechanism. The same types of entities are also the subject of the study of Hałaj (2018), who also include contagion mechanisms eligible liquidity buffers, interbank funding, fire sales, funding cost and solvency, information contagion, and default risk, with more detailed breakdowns in the funds sector introduced in Mirza et al. (2020). Banks and investment funds are modelled also by Roncoroni et al. (2021) and Sydow et al. (2024). Additional institutions are modeled in other works. While Farmer et al. (2020) propose a system-wide financial stress testing framework for banks, investment funds and hedge funds, Aikman et al. (2019) look at the interaction of banks, investment funds, hedge funds, money market funds, and also pension funds and insurers as well as the effect of asset sales and overlapping portfolios in a representative agent framework. A wider financial system of banks, open-ended funds and insurers is also considered in Caccioli, Ferrara, and Amanah (2020) focusing only on fire sale contagion. Franch, Nocciola, and Vouldis (2024) investigate both numerically and visually the temporal evolution of financial contagion networks across the banking, shadow banking and insurance sectors of 18 advanced economies. The authors find that banks are the main source of financial contagion and are highly interconnected with shadow banks: during the global financial crisis contagion from insurances was at its highest. While Calimani, Hałaj, and Żochowski (2019) propose a theoretical framework, most of the cited works exploit granular, real-world data (Hałaj, 2018; Caccioli, Ferrara, and Amanah, 2020; Farmer et al., 2020; Roncoroni et al., 2021; Franch, Nocciola, and Vouldis, 2024). Falter et al. (2021) model market risk scenarios and amplification effects for banks, funds and insurers mainly with asset side dynamics of the sectors. However, none of these papers model the liability side of insurance companies. According to our knowledge, this paper is the first one to fill this gap in the literature.

Another strand of literature investigates empirically the interaction between liquidity and solvency shocks. While the topic has been widely studied (Imbierowicz and Rauch, 2014; Pierret, 2015; Basel Committee on Banking Supervision, 2015; Schmitz, Sigmund, and Valderrama, 2019), a number of empirical studies more similar to ours have recently come to light. Hałaj and Laliotis (2017) discuss the extent to which solvency shocks can be magnified by liquidity crises and conclude that modelling the compounding effects of solvency and liquidity risks can improve our understanding of banks' funding shocks. Hesse et al. (2012) study the connection between these two risks by simulating a sudden increase in funding expenses due to heightened solvency concerns, the exclusion from the funding market due to low capitalization levels and high concentration risk. Cont, Kotlicki, and Valderrama (2019) propose a joint framework where solvency shocks influence liquidity via margin requirements, short-term funding, and credit risk sensitive outflows. The resulting endogenous liquidity shocks reinforce solvency stress due to heightened cost of new funding and fire sales.

Our contribution to this literature is the introduction of a stress test model, which extends beyond the banking sector (Alessandri et al., 2009) and investment funds (Sydow et al., 2024; Budnik et al., 2024). With the inclusion of insurance companies, our three-sector framework can more realistically reconstruct inter-institutional exposures to study interconnectedness effects via portfolio holdings, which include euro area securities holdings and loan exposures. Insurers' can trigger or amplify systemic risk, through their exposure to liquidity risk, interconnectedness, and limited substitutability, which propagates through asset liquidation, exposures and disruption of critical function.[1] Our novel liability-side approach for insurers models the loss absorbing capacity of technical provisions in the life business, estimated from confidential firm-level data. Since life insurance contracts may have embedded profit participation, policyholders bear the risks of financial assets held to some extent. In addition, we also take into account the effect of interest rates on the discounting of future cash flows, which brings an additional impact on the levels of technical provisions of insurers.

The literature specifically on insurance stress testing is scarce, but relevant papers already consider the liquidation channel as an important source of risk (Berdin and Gründl, 2015; Grochola, Gründl, and Kubitza, 2023; Girardi et al., 2021). Regarding liability side mechanisms, Berdin and Gründl (2015) and Grochola, Gründl, and Kubitza (2023) model future cash flows of insurers and adjust technical provisions following financial market shocks.

We recreate both the liability and asset side of the entities in the financial system by merging different databases. In our model, we first stress the asset side of financial institutions via a macro-financial scenario[2], which generates a first-round of initial losses on the balance sheets of banks, funds and insurers through their exposures to credit and market risk. In a second step, agents

[1] Ref. to IAIS (2019) Holistic Framework for Systemic Risk in the Insurance Sector. Available at: https://www.iaisweb.org/uploads/2022/01/191114-Holistic-Framework-for-Systemic-Risk.pdf

[2] NGFS 2050 hot house world scenario.

react to the initial shock triggering a series of simulated endogenous reactions, which, through an endogenous propagation channel and interconnections among sectors, lead to second-round losses. Endogenous reactions include fire sales mechanisms of overlapping portfolio exposures at the institution-level. The main contagion channels are liquidity and solvency risk, mainly embedded in securities' cross-holdings and overlapping portfolios. As a result, banks, funds and insurers contribute by amplifying or absorbing initial losses in the system.

The rest of the paper is organized as follows. Section 2 outlines the datasets employed to conduct the analysis in addition to relevant key empirical evidence on the three financial sectors and their interconnections. Section 3 introduces realistic shocks to the system from satellite models. Section 4 provides an overview of the financial system of banks, funds and insurers, their sectoral risks and constraints, their relevant balance sheets items, and defines the specifics of the model and its dynamics. Section 5 discusses results of the model. Section 6 draws conclusions.

Appendix A introduces mathematical and balance sheet notations. Appendix B shows visual information on the loans and securities exposure networks within the system. Appendix C outlines sectoral regulatory information, appendix D elaborates on insurance modelling background information, appendix E shows background results from simulations.

2 Data and sector coverage

Our network configuration includes three types of entities: banks, investment funds and insurers. In the banking sector we have 166 large consolidated banking groups, 10,555 open-ended funds in the investment fund sector, and 18 country-level company aggregates for the insurance sector, all domiciled in the euro area. In the following paragraphs, we lay the foundations by introducing our financial system of banks, funds and insurers, and their balance sheet composition.

2.1 Banking sector

Our stylized banking system reconstructs the bank-to-bank and bank-to-non-bank network exposures. Consolidated banking groups hold portfolios of loans, tradable securities and redeemable fund holdings on their assets side, while on their liabilities side, interbank liabilities are included together with issued tradable securities. Table 1 shows an aggregate balance sheet representation of euro area banks.

Banks

Securities and fund shares	2.83	Capital	1.28
Loans	15.56	Issued securities	0.54
Other Assets	5.71	Interbank Deposits	0.37
		Other Deposits and Liabilities	21.91
Total assets	***24.1***	***Total liabilities***	***24.1***

Table 1: Banks' modelled balance sheet (numbers given in trillions of euros).
Source: ECB COREP, FINREP and SHS-G data.

The banking sector balance sheets are built on highly granular information on exposures of euro area banks to single entities in the real economy. Our dataset includes granular data about significant and less significant institutions.[3] Banks' portfolios are primarily constructed using the COREP dataset that incorporates the Large Exposures Framework within the euro area. Thus, credit institution information on bilateral exposures towards the real economy are included at the counterparty level. Residual exposures are embedded at the country-sector level by calculating the difference among FINREP aggregate exposures and the total exposures reported at the granular level. Lastly, security holdings information at the ISIN-level are incorporated by adding data from SHS-G for each banking group. Derivatives positions are not included at this stage.

Banks are constrained by their regulatory and contractual obligations, which are discussed in Section 4.1.1. Regulatory obligations include liquidity and solvency requirements, which are implemented via distress and default thresholds calibrated at bank-level using COREP data and capital information provided by national authorities in the European System of Central Banks (ESCB).

2.2 Investment funds sector

The fund sector consists of open-ended investment funds which include equity, bond, and mixed funds. Funds' assets consist primarily of securities along with deposits and claims, non-financial assets and remaining assets. Funds' liabilities include mostly fund shares, acquired by investors, and to a more limited extent, loans. Table 2 shows the aggregated balance sheet of euro area investment funds that are covered by our model.

Investment funds

Deposits and cash	3.41	Investment fund shares	8.21
Securities and fund shares	4.86	Loans	0.05
Total assets	***8.27***	***Total liabilities***	***8.27***

Table 2: Investment fund's modelled balance sheet (in trillions of euros).
Securities are a combination of equities, debt securities and fund shares. Cash is included in the 'Deposits and claims' category.
Source: Lipper IM and authors' calculations.

The fund sector balance sheets are built using highly granular information about exposures of euro area funds. Funds' portfolios are constructed on the basis of balance sheet information as provided in Lipper IM by Refinitiv. For more than 1500 of funds we have sufficiently complete information on their balance sheet, which allows us to treat these funds as active agents in our model, while the remaining funds are identified as counterparties and not active in the model.

Investment funds are intertwined and highly connected to the broader financial system. Due to the absence of related regulation, no distress thresholds are considered, and a default threshold discussed in Section 4.1.2 is synthetically defined from available balance sheet information. Given that investors can redeem fund shares on demand, these redemptions have a severe impact on individual fund liquidity, which is mitigated by the selling of assets and redemption of other fund

[3] Less significant institutions are banks that do not fulfil any of the significance criteria specified in the SSM Regulation – in contrast to significant institutions that do fulfil at least one of them. They are supervised by their national supervisors, under the oversight of the ECB, whereas significant institutions are directly supervised by the ECB.

shares held. In addition, fund balance sheets are typically not highly leveraged, thus insolvencies are unlikely to occur.

2.3 Insurance sector

The modelling of the insurance sector's the balance sheet is conducted with information aggregated at the country-level for life insurance solo undertakings within the euro area, stemming from the lack of available individual entity level information. These data are then supplemented with highly granular securities holdings of insurers towards other agents in the system. Table 3 shows the aggregated balance sheet of euro area insurers that are covered in the model.

Insurance solo undertakings

Securities	5.82	Own funds/Equity	1.42
Cash deposits	0.09	Issued securities	0.05
Other Assets	3.23	Loans	0.02
		Obligations towards policyholders	5.79
		Other Liabilities	1.86
Total assets	***9.14***	***Total liabilities***	***9.14***

Table 3: Aggregated life insurance solo undertakings' modelled balance sheets (in trillions of euros).
Source: Solvency II and SHS-S data and authors' calculations.
Note: The table represents a stylised aggregated balance sheet of the sector and it does not reflect the full granularity of the Solvency II balance sheet (e.g., obligations towards policyholders only encompasses those stemming from life portfolios excluding health and non-life).

The dataset thus includes granular data coming from Securities Holdings Statistics by Sector (SHS-S) data at the ISIN-level in combination with EIOPA Solvency II data at country-level aggregation. The latter, which cover insurers' cash and cash equivalents, total assets, technical provisions, own funds and solvency capital requirements, are sourced from Balance Sheet, Own Funds and Solvency Capital Requirement - Market Risk templates, (see Table 15 for a detailed overview). Importantly, these data are used in the regression analysis described in Appendix D.1 which facilitates our approach to Loss Absorbing Capacity of Technical Provisions of insurance solo undertakings aggregated at country level, as outlined in Sections 4.3.1 and 4.3.2.

In addition to these major data sources, to fill in the data gaps in the modelling of insurance undertakings, we employ data published by EIOPA to approximately quantify effects related to insurance liabilities. More specifically, in our approach to model interest rate shocks on the liability side of insurers, as detailed in Section 4.3, we use country-level approximate effective durations and Macaulay durations of liabilities, available in Table 13, which we take from EIOPA (2016)[4]. Moreover, in order to apply an exogenous lapse shock on the liability side of insurers, as explained in Section 3.4, we incorporate country-level mass lapse exposure rates for insurance with profit participation as well as index-linked and unit-linked insurance from EIOPA (2019)[5].

[4]See Table A II. 1 on page 60
[5]See Annex 1 on page 176

In the model, insurance undertakings are bound by their solvency capital requirement and undertake asset fire sales if such requirement is breached or they face liquidity shortfalls due to surrenders of insurance policies. Their constraints are discussed in detail in Section 4.1.3.[6]

2.4 Interconnections between sectors

The identification of entities and the group consolidation represent the final steps in building our dataset. First, a unique identification code is assigned to each reported counterparty in the system by implementing an auxiliary database. The specific LEI (Legal Entity Identifier), RIAD (Register of Institutions and Affiliates Data) and ISINs (International Securities Identification Numbers) are extrapolated from Moody's, GLEIF (Global Legal Entity Identifier Foundation) and CSDB (Centralised Securities Database) databases to uniquely identify each issued security and the corresponding issuer. Second, a tailored data-matching procedure makes it possible for all the entities in the sample to be included under the network nodes to which they are related.

The sectors are linked by means of multiple interconnections. Indeed, banks lend to investment funds and insurance undertakings. Furthermore, those three sectors also hold each other' securities. Data on banks' loan exposure to large exposures at the counterparty-level to both financial and non-financial corporates are obtained from large exposure reporting and ISIN-level information from Securities Holdings Statistics (SHS).

As illustrated in Figure 1, it is notable that insurers are the primary holders of investment fund shares and securities issued by governments and banks. This observation led to the development of the liquidity shock scenario, where insurers become active in the market when confronted with a redemption shock (see Section 3.4).

3 Scenario and exogenous shocks

For an illustration of the methodological contribution of this paper, we consider a NGFS 'hot house world' transition scenario featuring an increase in credit risk losses and an instantaneous market shock leading to asset price devaluations. Also, we concentrate on the short-term implications of the materialisation of such a transition scenario and not the long-term effects over several decades. This is combined with an add-on scenario of liquidity shocks applied to all sectors in the form of interbank funding withdrawals, fund redemptions and insurance surrenders.

While climate change is now recognized in the field of financial supervision (NGFS, 2020), the climate stress testing literature is still a growing field with a link to the more methodological literature on system-wide stress testing that we outlined in the introduction of this paper. In line with Stern and Stiglitz (2022) and Lamperti et al. (2019), who claim that implications of climate change can be better understood once the entire financial system is properly considered, Battiston et al. (2017) adopt a network-based framework and find that investors' equity portfolios for investment and pension fund are especially exposed to climate-policy-relevant sectors and that a timely transition would produce a non-adverse adjustment in asset prices. Similar conclusions are reached by Roncoroni et al. (2021), who find that in a system of banks and investment funds losses increase if a disorderly transition occurs later, or if a financial sector is more exposed to high-carbon sectors. Market conditions also play a significant role and have the potential to mitigate losses from a larger climate-related shock. To study these systemic implications of climate-related market failures, Gourdel and Sydow (2022) develop a short-term climate stress-test model, built on transition and physical risk exposures between funds and firms. Jourde and Moreau (2022) find

[6]The Solvency II Solvency Capital Requirement (SCR) is not modelled, hence kept constant.

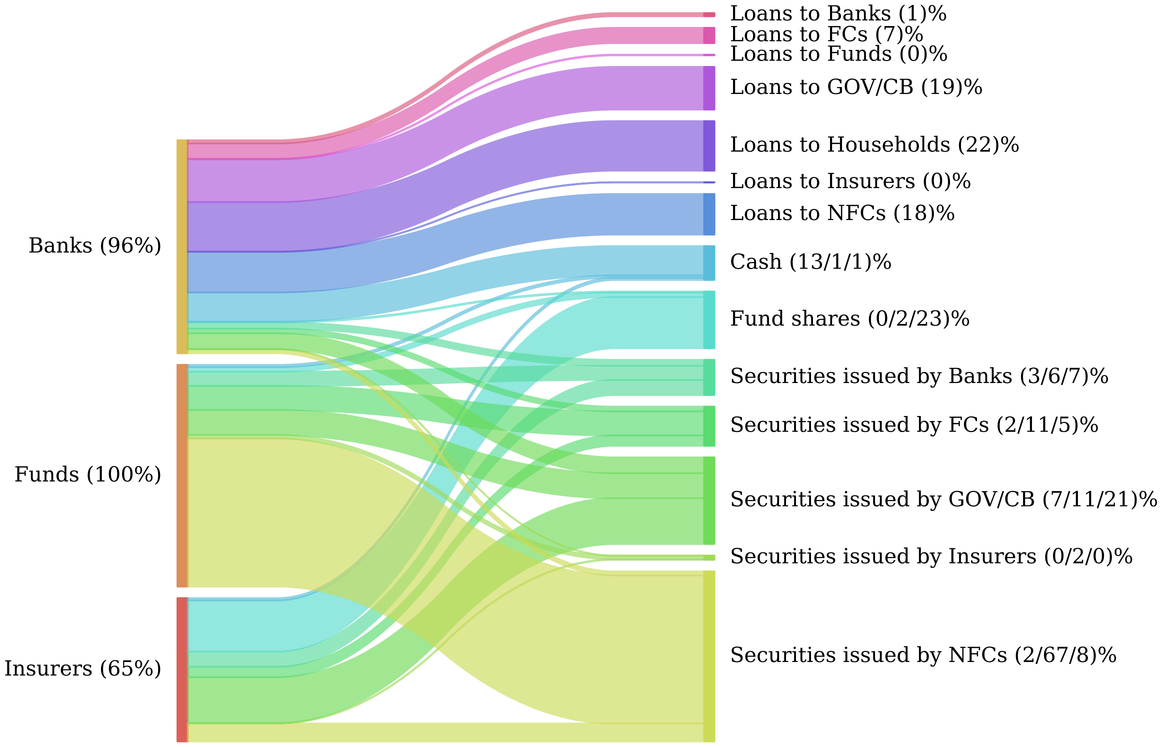

Figure 1: Sankey chart of exposures covered in the model.
Right-hand side elements show the system's asset holdings. The percentages in brackets express the share of exposures in the balance sheets of banks, funds, and insurers, respectively. The coverage of assets can be below 100%. Percentages in brackets shown on the left-hand side indicate the overall sectoral asset coverage.
Source: Authors' calculations.

that especially life insurers and real estate investment trusts are significantly exposed to transition climate risk, although banks have also increased their exposure to this risk since 2015. Climate risk is also found to be relevant from a macroprudential perspective in that it is found to intensify tail dependence among financial institutions. Lastly, Lamperti et al. (2019) find that climate change will lead to more frequent banking crises; rescuing these banks will lead to an increased fiscal burden and the doubling of the public debt, although macroprudential policies can mitigate rescuing costs.

Despite the fact that our paper is mainly about the methodological contribution regarding the liability side modelling of insurers' balance sheets under stress, our work provides as well a stylised contribution to the existing literature of climate risk stress testing by quantifying hypothetical scenario-conditional first-round losses in our financial system with highly interconnected banks, funds and insurers and possible second-round amplification effects. Thus, this paper investigates the impact of a severe macro-financial shock using a scenario from the Network for Greening the Financial System (NGFS).[7]

NGFS scenarios formalise the impact of climate change (NGFS, 2020) on a number of financial and macroeconomic factors, which are linked to agent-specific risk factors. These scenarios lay out specific assumptions regarding how climate policy, emissions and temperatures are expected to change. For example, the orderly transition scenario prescribes future pathways consistent with limiting the increase in global average temperatures to significantly less than two degrees Celsius above pre-industrial levels.

Concretely, we consider a hot house world (current policies) transition scenario, which assumes that only currently implemented policies are preserved and that only some countries implement climate policies, while the rest of the countries make insufficient efforts to stop global warming (NGFS, 2021). While non-life insurers would be predominantly affected by a 'physical' climate risk scenario, it is important to note that our analysis captures only a 'transition' risk scenario that is affecting the value of assets of insurers, which is not limited to the non-life business of insurers.

Climate change affects the wider financial system, and extends beyond banking institutions (Lamperti et al., 2019; Roncoroni et al., 2021; Stern and Stiglitz, 2022; Dubiel-Teleszynski et al., 2022; Gourdel and Sydow, 2022; Jourde and Moreau, 2022). The impact of the climate scenario on the balance sheet of investment funds and insurance undertakings is calculated by integrating the results of the 2021 climate stress test conducted by the European Securities and Markets Authority (ESMA) and the European Insurance and Occupational Pensions Authority (EIOPA) for the NGFS scenarios. For investment funds, the scenario is based on the country- and sector-level bonds and equities valuations, which affect funds' assets under management (see ECB/ESRB, 2021); for insurance companies, the scenario translation affects the valuation of bonds and equities linked to sectors that are more exposed to climate risks, such as power generation and the extraction of fossil fuels (see ECB/ESRB, 2021).

3.1 Credit risk shock – solvency shock

The ECB economy-wide climate stress test represents the foundation for the scenario-conditional credit risk parameters (Alogoskoufis et al., 2021) used in our work. The estimated credit risk parameters are conditional on the hot house world scenario and specifically assesse the impact of transition risks onto individual non-financial corporations' (NFC) profitability, leverage, and ultimately, credit risk.

The impact of a NGFS scenarios on the banking sector is determined by incorporating credit

[7] See the website of the Network for Greening the Financial System.

risk parameters from the real economy, with probabilities of default (PDs) and loss given default (LGDs) for NFCs available at the country and NACE-2 level[8]. All other exposures are assumed to be shocked by taking starting point COREP PDs and LGDs into account, i.e. not in a scenario-conditional manner. This shock has an impact on expected losses for banks, which, after provisions and income are taken into account, can deplete their capital.[9] Scenario-conditional PDs and LGDs for NFCs are independent of the market shocks for asset holdings.

3.2 Market shock – solvency shock

To define the initial market shock, we use NGFS-conditional initial asset devaluations, as calculated by EIOPA and ESMA for ECB/ESRB (2021), reported similarly at the country and NACE-2 level.

The shock leads to revaluations of securities and consequently fund holdings of all sectors in the system. In addition, when risk-free interest rate shocks are provided by the scenario, technical provisions (liabilities of insurers) are also updated using aggregate durations of liabilities.

3.3 Redemption shock – liquidity shock

A flow-performance relationship is used to derive scenario-conditional redemptions based on the initial price changes of funds due to the exogenous market shock. The price formula is derived in line with Sydow et al. (2024)[10], flow-performance coefficients are based on Baranova et al. (2017), Baranova, Douglas, and Silvestri (2019) and Aikman et al. (2019). In attaching the coefficients to individual funds, we apply the look-through approach defined in section 4.3.3 to determine the share of government bonds, corporate bonds and equities in the portfolios of investment funds. We assume that these exogenous redemptions are from external investors outside the modelled financial system (as in Sydow et al., 2024):

$$r_{i,t} = \rho_i \cdot \left(\overbrace{\sum_j h_{i,j}^{\text{bnd}} + h_{i,j}^{\text{eq}} + \sum_j h_{i,j}^{\text{fnd}} + c_i - \sum_j l_{j,i} - \sum_j h_{j,i}^{\text{fnd}}}^{\text{external investors' holdings}} \right), \tag{1}$$

where redemption rate $\rho_i = \varphi_i \cdot (p_{i,t} - p_{i,t-1})$ is a function of the funds' price change with flow-performance coefficient φ_i, $t-1$ and t are discrete moments in time right before and after the exogenous market shock (see Appendix A for an explanation of the balance sheet notations used in the equations). Cash holdings of each fund are then updated using the redeemed amount:

$$c_{i,t} = c_{i,t-1} - r_{i,t}. \tag{2}$$

This liquidity shock leads to liquidity shortfalls for funds, which are then closed by redeeming other fund shares and selling securities proportionally to their holdings ('Second-round effects' in Figure 2).

3.4 Surrender shock – liquidity shock

Surrenders refer to insurance policyholders' cancellations of their contracts, which result in policyholders' redemptions of their accumulated wealth from insurers. This shock is unrelated to the NGFS scenario and based on ad-hoc assumption for an illustration of this modelling feature. Surrenders can materialise in an environment of rising interest rates, where short term investment

[8]Statistical Classification of Economic Activities in the European Community.

[9]In a stochastic simulation setup used in Sydow et al. (2024), the credit risk shock has an impact also on the portfolio holdings of all sectors, via price devaluations of defaulted corporations.

[10]See equation (15) in the cited paper.

options offer higher return than long term insurance investment products. Under this scenario policy holders might opt to switch their investment-based policies with low biometric coverage to more attractive opportunities, cancelling existing contracts agreed during a phase of lower interest rates.

The surrender rate is introduced in this work as a sensitivity parameter, while the share of technical provisions subject to surrender are available in Table 14 and based on publicly available data from EIOPA. Surrender values are calculated as the lapse exposure rates multiplied by technical provisions for life and unit linked businesses:

$$s_{i,t} = \xi_i \cdot \left(\overbrace{EXP_i^{\text{life}} \cdot TP_{i,t}^{\text{life}} + EXP_i^{\text{UL}} \cdot TP_{i,t}^{\text{UL}}}^{\text{technical provision exposed to mass lapse}} \right), \tag{3}$$

where ξ_i is the surrender shock. The cash of insurers is then similarly updated:

$$c_{i,t} = c_{i,t-1} - s_{i,t}. \tag{4}$$

Because of this initial liquidity shock, insurers are forced to redeem their fund shares and sell securities proportionally to their holdings ('Second-round effects' in Figure 2). However, due to the loss absorbing capacity of insurance undertakings, the impact on the liability side of insurers' balance sheets is somewhat dampened (Section 4.3 will explain this feature in detail).

4 Model overview

In this section, after referring to the general model dynamics from the previous system with banks and funds (see Sydow et al., 2024), we focus on extensions coming from the newly added insurance sector. The inclusion of both investment funds and insurers in a network model aimed at assessing systemic vulnerability of the financial sector is novel and a paramount step on the path to understand contagion channels within the entire system. For a list of notations, see Appendix A.

4.1 Sectoral risks and regulatory constraints

4.1.1 Banks

The banking sector includes banking groups operating as stand-alone institutions with an individual balance sheet; their level of consolidation is presented in Section 2. In our model, the behaviour of banking groups is guided by the need to meet regulatory constraints, i.e. solvency and liquidity needs. The latter arise following contractual obligations and prudential liquidity regulation. Moreover, agents are not optimizing their risk exposure amounts (REA), e.g. by deleveraging, which is the denominator in the calculation of banks' capital ratios.

Table 4 presents a summary of the sectoral risks arising from the banking sector and the regulatory constraints included in our model. For detailed information see Appendix C.1 and Sydow et al. (2024).

4.1.2 Investment funds

The investment fund data set covers of open-ended investment funds. These funds are financed through shares acquired by investors, which can be redeemed—sold back to the funds—upon request, thereby ensuring high liquidity of the fund shares. On the other hand, funds invest in assets

Sectoral risks

Risk type	Description
Direct contagion via credit risk and bank defaults	Liability side of defaulting entities and expected losses
Solvency-liquidity feedback loop	Solvency distress leads to short-term funding shocks
Direct contagion via market risk	Bond, equity prices and fund holdings
Indirect contagion via market risk	Price impact from asset fire sales and overlapping portfolios

Regulatory constraints

Solvency capital requirements	Definition
Solvency distress threshold	TSCR (Total SREP Capital Requirements)
Solvency default threshold	Pillar 1 and 2 requirements
Prudential liquidity regulation	**Definition**
Liquidity distress threshold	HQLA level for 100% LCR
Liquidity default threshold	HQLA = 0

Table 4: Banks' sectoral risks and regulatory constraints.
'SREP' refers to the ECB Supervisory Review and Evaluation Process.

of longer maturities and lower liquidity such as corporate bonds. Investment funds are exposed to different risk factors, depending on their type: maturity and liquidity mismatch, concentration and leverage. Despite of individual differences in investment strategies and, thus, exposures to different risk factors, investment funds are in general interconnected with one another and with the rest of the financial system, on both sides of their balance sheet. Therefore, faced with market stress, they can transmit shocks to the financial system and generate feedback loops. Funds are mainly equity-financed and do not borrow large amounts from banks. Hence, funds defaults are a very rare phenomenon. Open-end funds are governed by dynamics that require a number of assumptions, in particular regarding the timing and volume of redemptions. As detailed later in the text, redemptions can either be endogenous, i.e. from other explicitly modelled financial institutions, or exogenous.

Table 5 presents a summary of the sectoral risks for the investment fund sector and the constraints included in the model. For detailed information see Appendix C.2 and Sydow et al. (2024).

4.1.3 Insurance undertakings

The role of insurers in the financial system and in the economy is to provide long term funding and to provide protection to policyholders. In this work, we neglect for insurance companies outflows related to insurance claims and benefits. Figure 1 confirms that since insurers are large holders of investment funds and issued securities, their response to shocks impacts all other sectors. Insurers are also exposed to liquidity risk via policyholders' surrenders. In the normal course of business, insurers use cash reserves, liquid assets and inflows to cover surrenders. In the model, we assume that there are no inflows and that surrender shocks exceed normal levels. Redemptions are therefore considered as net outflows covered only by balance sheet assets because, in any case, the liquidity reserve must be replenished after the transactions.

Sectoral risks

Transmission channels	**Description**
Asset liquidation channel	Funds are forced to liquidate securities when they face a significant redemption shock
Direct exposure channel of fund shares	Counterparties holding fund shares would be affected by a decrease in Net Asset Value (NAV)
Direct exposure channel of loans	Banks that finance funds suffer losses in case of a fund default
Direct contagion via market risk	Bond, equity prices and fund holdings
Indirect contagion via market risk	Price impact from asset fire sales and overlapping portfolios

Solvency and liquidity thresholds

Solvency threshold	**Definition**
Solvency default condition	Capital (Total Net Assets) < 0
Liquidity threshold	**Definition**
Liquidity default condition	Cash < 0

Table 5: Investment funds' sectoral risks and regulatory constraints.

Solvency II insurance regulations assess market risks based on market value, valuing assets at market prices and liabilities using the EIOPA curve to discount expected outflows. Thus, fluctuations in financial markets directly impact own funds. More precisely, The relationship between assets and liabilities depends on contract types and can be simplified for clarity as follow: (i) Unit-linked policies offset liability with asset variations, transferring risk directly to the policyholder. (ii) Conversely, defined-benefit life contracts expose insurers to market value loss risk without altering liabilities. (iii) Profit-sharing clauses in common contracts adjust liability values in response to asset loss converted in futur profit reductions. This mechanism is reflected in the called loss-absorbing capacity of technical provisions (LAC TP).

Table 6 summarises the relevant risk channels and regulatory constraints.

4.2 Model dynamics

The objective of our model is to examine the short-term dynamics and granular response of a network of banks, funds, and insurers in relation to a macro-financial shock scenario. Figure 2 summarises the model dynamics, which build on the two-sector implementation. The most important insurance-specific extensions are highlighted in green boxes.

Looking at 'first-round effects', our analysis focuses on the financial effects of an exogenous macro-financial stress test scenario, which is linked to sector-specific risk factors, via ECB satellite models. The scenario produces initial shocks, which propagate via the credit, liquidity and market risk channels. Banks are most vulnerable to credit risk losses due to their exposures to households, non-financial corporations (NFCs) and financial corporations (FCs) and other sectors.

The initial shock further produces changes in the valuation of securities holdings (using the 'Financial Shock Simulator', see ECB, 2019) within the whole model, where investment funds and insurance companies hold the majority of securities issued by NFCs, FCs, and other sectors. Additionally, funds' assets and liabilities are linked in that a decrease in a fund's Net Asset Value

Sectoral risks

Risk type	Description
Asset liquidation channel	Insurers are forced to liquidate securities when they face a significant surrender shock (Berdin, Gründl, and Kubitza, 2017)
Direct exposure channel of loans	Banks that finance funds suffer losses in case of a fund default
Direct contagion via market risk	Bond, equity prices and fund holdings
Indirect contagion via market risk	Price impact from asset fire sales and overlapping portfolios
Changes in liabilities (technical provisions)	Changes in the interest rate environment lead to changes in the amounts of technical provisions via the discounting they use; impact on solvency

Regulatory constraints

Solvency capital requirements	Definition
Solvency distress threshold	SCR (Solvency II framework)
Solvency default threshold	MCR (Solvency II framework)
Liquidity regulation	**Not yet covered by the regulatory framework**

Table 6: Insurance companies' sectoral risks and regulatory constraints

(NAV) is assumed to affect counterparties holding funds' shares ('Price equilibrium'). When prices are updated for all securities and holdings, funds' returns are also updated, which are then used to derive initial outflows ('Redemptions') from funds, using flow-performance coefficients.

Constant surrender rates are applied on the reported, country-specific surrender values for the insurance undertakings covered in this paper ('Surrenders'). It should be noted that for insurers, the potential adjustment in the asset pricing is partly transferred to policyholders, and that the value of the liabilities is also adjusted by the movements in the risk free rate.

The granular interconnections of entities and sectors are depicted in two figures in the Appendix B, Figure 12 shows a representation of the entity-level network of the banking sector's loan exposures. Figure 13 illustrates the network of granular securities cross-holdings among our banks, funds, and insurers. These interconnections are sources of amplification of the shocks in the second block of the model.

Looking at 'Second-round effects' in Figure 2, agents are assumed to take actions, which can exacerbate the initial impact. Endogenous reactions start with a first update of the solvency status of all agents, which can result in defaults and in further changes in equilibrium prices of funds. In response to credit and market risk losses, agents have a number of options to meet their liquidity needs. These options start with interbank liquidity withdrawals and the possibility of unsecured borrowings for banks. Short-term funding is withdrawn from/by distressed or defaulted banks, potential remaining liquidity gaps are closed by a proportional withdrawal of remaining interbank assets. Then, if there are still banks having liquidity needs and if they are solvent, they are able to take short-term unsecured interbank loans from other liquid and solvent banks. The latter represents a liquidity inflow but without causing any costs for the borrowing bank.

After this, all sectors are able to redeem fund shares and to sell securities to close remaining

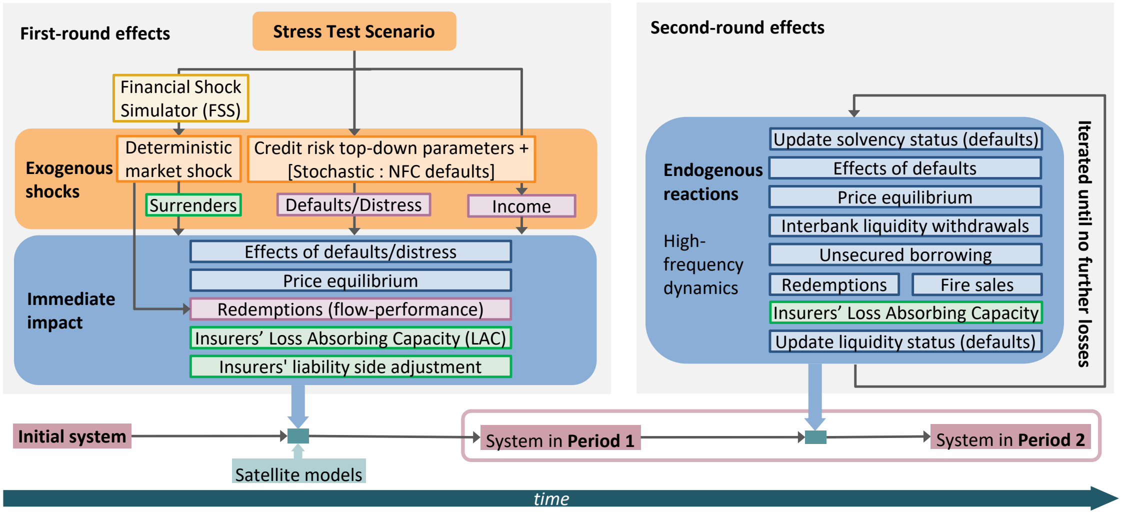

Figure 2: Summary of model dynamics.
Note: green boxes are new features of the model, all other blocks are described in detail in Sydow et al. (2024).

liquidity gaps. Redemptions and fire sales[11] are proportional to the entities' holdings, in a way that sold/redeemed amounts do not change the distribution of the portfolio of the entities. With the addition of insurers, who hold large amounts of fund shares, the role of fund redemptions is significant when investigating second-round scenario-conditional losses.

At the end of one iteration round, the liquidity status is updated for all entities, and the procedure continues until no further losses arise in the system. Since the number of entities, who can default is limited, and price decreases have a lower bound, the iteration converges in finite steps.

In sum, the model runs iteratively against a specific macro-financial scenario, which leads to first-round default (credit) and market losses. Our banks, funds and insurers respond to these shocks ('Second-round effects'), and continue to do so depending on their evolving solvency and liquidity status. Importantly, our modelling framework captures only a reduced-form perspective of the behaviour and activities of the three agents in our modelled financial system, e.g. securities financing transactions or derivatives are not captured. Moreover, the Solvency II regime is applying a fully marked-to-market accounting approach, which implies that a direct comparison of insurers' and banks' market losses is not always possible given that some bank portfolios are based on historical cost accounting. However, the model can still provide some first insights on how these markets interact in an episode of financial distress.

4.3 Insurance-specific model extensions

This section elaborates on the model extensions related to insurance sector specific modelling. These new features are centred around the fact that insurance undertakings are able to transfer part of their losses to policyholders. This mechanism is called Loss Absorbing Capacity of technical provisions (LAC TP) (see EIOPA, 2015). We derive this capacity at the aggregate country level,

[11] Across all the simulations, we use price impact quantiles as functions of sold volumes estimated for the 5th percentile, see Fukker et al. (2022).

based on certain assumptions, and separately for exogenous and endogenous losses arising in the model. Additionally, a duration-based methodology is applied to both the asset and liability side (effective duration) at different levels of granularity, allowing to adjust bond valuation at security level (by issuer) and the overall size of technical provisions for life insurance products which have longer maturity.[12]

4.3.1 Loss Absorbing Capacity of insurance undertakings

In contrast to other financial institutions, liabilities of insurers, accounted within the Solvency II framework, consist of discounted future cash flows to policyholders, i.e. the best estimates which is considered as equivalent to technical provisions in this paper.

In response to a market shock, life insurers' own funds does not necessarily decline by the same amount as the value of their assets, because liabilities can absorb (at least partly) the loss of assets. Indeed, for profit-sharing life insurance contracts, the expected discretionary profit sharing distributed to policyholders may be reduced when the insurer experiences a decline in the market value of assets. In contrast, for unit-linked insurance contracts, the policyholders bear the entire risk of loss of value of the assets. Hence, the asset side and liability side are connected and the effect on own funds is derived by taking both changes into account. Since we are focusing on macro-financial risk scenarios, we develop a method for assessing the impact of a shock on equity and bond holdings.

To model the LAC TP in our system-wide stress test model, we use an approximation which relies on reporting data from the Solvency II standard formula. Figure 3 describes the mechanics of the LAC TP approach for an entity i, given for example, an equity price shock. The x-axis of Figure 3 shows the loss in asset values,

$$\Delta A_i = \left(\sum_{\phi} \left(h_{i,\phi,t} - h_{i,\phi,t-1} \right) \right)^{-} \geq 0$$

where $f^{-} = \max(-f, 0)$ and ϕ can be the set of equities or bonds depending on the risk category we are interested in, $h_{i,\phi,t}$ is the holding of security ϕ by insurer i at time t. Specifically, $\Delta A^{SII}_{i,Equity} \geq 0$ is the loss in asset values that the considered insurer reports for the equity price shock defined by the Solvency II standard formula specification. The y-axis shows the decrease in liability values, ΔL_i, in consequence of this loss of asset value.

Two opposite cases are then presented: if a loss in equities, $\Delta A_{i,Equity}$, can be fully transferred to policyholders (this would apply, for instance, if all equity values were attributed to unit linked insurance contracts), then the combination (ΔA_i,ΔL_i) lies on the bisector (dashed blue line where $\Delta L_i = \Delta A_i$). In this situation, the insurer's own funds would not be affected by the equity price shock. However, if the loss in equities cannot be transferred to policyholders at all (theoretical example of a defined benefit contract disregarding potential variations in the discounting curve.), then ΔL_i=0, and the combination (ΔA_i,ΔL_i) lies on the x-axis.

Indeed at insurer level, usually $0 < \Delta L_i < \Delta A_i$, which means that the equity price shock is only partly transferred to policyholders. The difference, ΔA_i-ΔL_i, is then the reduction in own funds following the shock on asset. For instance, as part of the Solvency II and SCR calculations, the asset type r shock is precisely defined and gives $\Delta A^{r,SII}_i - \Delta L^{r,SII}_i$, which represents the reduction in capital that insurers must be able to cope with for this type of asset. This loss is referred to as the SCR_r specific to this shock. Several shocks are thus defined, and all SCR_r are combined through a

[12]Non-life insurance is not considered in the model.

standard formula incorporating correlation between shock types. The aggregation yields the final SCR that insurers must be able to cover with own funds of a sufficient quality (also defined by the regulation).

This implies that Solvency II regulation generates a point on figure 3, enabling us to calibrate a conservative approximation of the differentiated technical provision absorption capacity for each insurer. Theoretically, the true relationship between ΔA_i and ΔL_i for the entity i must be concave (orange dotted lines in the figure) given that the LAC TP is more efficient for lower asset value reductions.

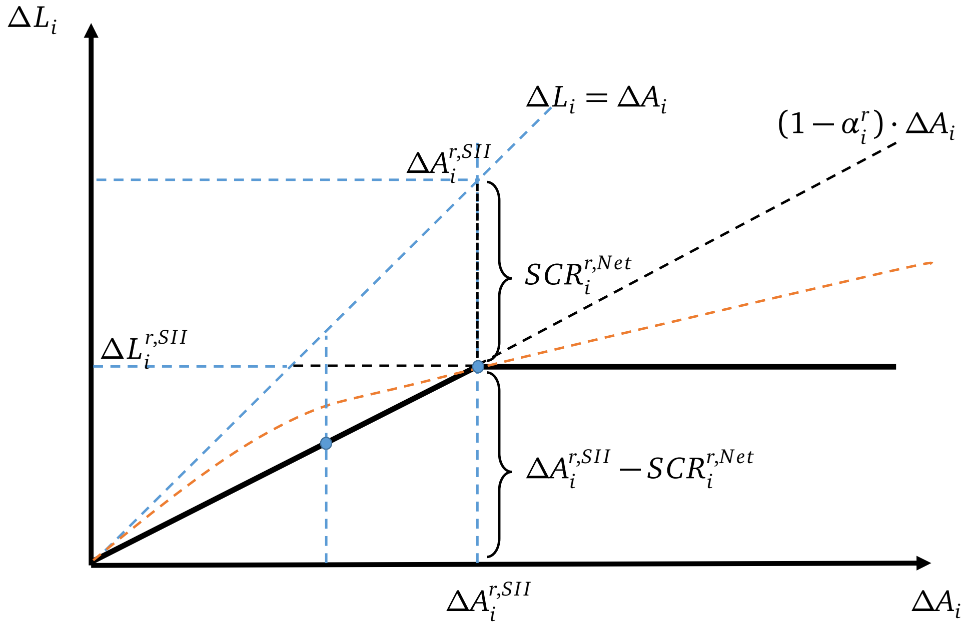

Figure 3: Stylized sketch of the LAC TP approach for an entity i and an exemplary market risk shock r: change in liabilities as a function of change in assets.

In our system-wide stress test, to be conservative, we introduce an upper bound on the change in liabilities and implement the LAC TP in terms of the thick black curve in Figure 3, and hence make use of a case discrimination. In the following, we consider an entity i and risk category r (such as equities, spread and property, but the actual implementation is done for equity only, assuming a 30% shock on equity prices). For asset value reductions ΔA_i^r smaller than $\Delta A_i^{r,SII}$ (case 1), we scale the LAC TP proportionally. For asset value reductions larger than $\Delta A_i^{r,SII}$ (case 2), we use the absolute amount of the LAC TP as reported in the standard formula. As said, the Solvency Capital Requirement reported is equal to

$$SCR_i^{r,Net} = \Delta A_i^{r,SII} - \Delta L_i^{r,SII}. \tag{5}$$

Furthermore, we assume that the SCR is a linear function (LAC TP is scaled proportionally) of the reduction in assets:

$$SCR_i^{r,Net} = \alpha_i^r \cdot \Delta A_i^{r,SII} \tag{6}$$

The central variable in case 1 is α_i^r, the percentage by which losses in the insurer's assets reduce the own funds according to the Solvency II standard formula:

$$\alpha_i^r = \frac{SCR_i^{r,Net}}{\Delta A_i^{r,SII}} \tag{7}$$

From equations (5) and (6), we get for the reduction of liability values:

$$\Delta L_i^r = \Delta A_i^r - \alpha_i^r \cdot \Delta A_i^r = (1-\alpha_i^r)\Delta A_i^r = \begin{cases} (1-\alpha_i^r)\Delta A_i^r & \text{if } \Delta A_i^r < \Delta A_i^{r,SII} \\ (1-\alpha_i^r)\Delta A_i^{r,SII} & \text{if } \Delta A_i^r \geq \Delta A_i^{r,SII} \end{cases} \tag{8}$$

which determines the thick black curve in Figure 3. Once the change in the liabilities is calculated, own funds are updated using the changes on both the asset and liability side:

$$k_{i,t} = k_{i,t-1} + \sum_r \Delta L_i^r - \sum_r \Delta A_i^r, \tag{9}$$

where $r \in$ {Equity risk, spread risk} and k the own funds.

The direct integration of this result into our model faces two impediments. Firstly, the data is solely available for insurers utilizing a standard formula, whereas the majority of major insurers employ their proprietary models. Therefore, extrapolating the sensitivity of standard formula users to aggregate country level, is a significant assumption (hence, limitation) of the model. Secondly, due to data confidentiality, access to granular insurance data is restricted. However, to partly overcome the limitation, EIOPA has cooperated in calibrating predefined model parameters. That said, a regression model was developed, tailored to model the specific absorption parameters of a (standard formula) insurer.

In fact, the core assumption of model suggests that the absorption effect remains unaffected by the company size, the formula (standard formula or partial/full internal model) utilized or other risk characteristics or even management actions, instead being solely contingent upon the types of contracts.

Our calibration of α_i^r follows the intuition that the loss absorbing capacity of an insurance undertaking is essentially driven by the size of its back-books of life insurance contracts with profit participation and of unit-linked insurance contracts. Moreover, the effectiveness of the LAC may vary substantially between countries due to country-specific features in the typical product design.

For each country-level insurance undertaking i and risk category r (equity risk or spread risk), we determine α_i^r using the following formula:

$$\hat{\alpha}_i^r = \beta_0^{r,\text{country}} + \beta_{\text{Life}}^{r,\text{country}} \cdot \text{Life}_i + \beta_{\text{UL}}^{r,\text{country}} \cdot \text{UL}_i$$

with Life_i denoting undertaking's Technical Provisions for Life Insurance (excluding Unit Linked Life Insurance) over Total Assets, and UL_i denoting Technical Provisions for Unit Linked Life Insurance over Total Assets.

We have empirically calibrated the coefficients $\beta_0^{r,\text{country}}$, $\beta_{\text{Life}}^{r,\text{country}}$, and $\beta_{\text{UL}}^{r,\text{country}}$ based on Solvency II data at the level of insurance undertakings. For seven major jurisdictions, we have estimated the coefficients using data of undertakings headquartered in that country; in addition, we estimated the coefficients based on all undertakings in the EU. Therefore, seven of our country-level model insurance undertaking are calibrated with coefficients from their country; the other model insurers are calibrated with EU-wide estimates. In all cases, the predictions $\hat{\alpha}_i^r$ have been restricted on the interval $[0,1]$, i.e. to be set to 0 if the regression result is negative or to 1 if the regression result is larger than 1. Details of the regression setup are described in Appendix D.1.

Estimation results are reported in Table 7 for equity risk and in Table 8 for spread risk (bonds). For the seven major jurisdictions, the coefficients are mostly significant and R^2 values seem plausible. EU-wide regression coefficients are used for countries with smaller sample size and implausible coefficients. Country names are not disclosed in the tables due to the confidentiality of the data used.

Equity risk (Type 1 equities)

	country							
	1	2	3	4	5	6	7	EU
β_{life}	-0.89***	-1.03**	-0.26	-0.76***	-0.72**	-0.64***	-0.77*	-0.68
	(0.05)	(0.45)	(0.19)	(0.05)	(0.28)	(0.19)	(0.44)	(0.04)
β_{UL}	-1.26***	-0.66	-1.14**	-1.24***	-0.75**	-1.06***	-0.97***	-1.05
	(0.12)	(0.39)	(0.43)	(0.10)	(0.28)	(0.15)	(0.21)	(0.04)
β_0	1.03	1.02	1.12	1.04	0.81	1.01	0.82	1.01
	(0.03)	(0.32)	(0.13)	(0.02)	(0.23)	(0.11)	(0.13)	(0.02)
R^2	0.82	0.21	0.23	0.80	0.24	0.61	0.50	0.54
obs.	91	24	28	129	29	34	26	569

Note: $^{*} p < 0.1$; $^{**} p < 0.05$; $^{***} p < 0.01$

Table 7: Regression results for type 1 equities.
Source: Authors' calculations.

Spread risk

	country							
	1	2	3	4	5	6	7	EU
β_{life}	−0.75***	−1.13***	-0.09	−0.58***	−0.76***	-0.38	-0.25	-0.53
	(0.05)	(0.39)	(0.07)	(0.05)	(0.17)	(0.23)	(0.33)	(0.03)
β_{UL}	−1.16***	−0.96***	−0.27*	−0.97***	−1.35***	−0.98***	−0.79***	-0.87
	(0.12)	(0.34)	(0.16)	(0.10)	(0.17)	(0.19)	(0.14)	(0.04)
const.	1.03	1.16	1.03	1.01	1.22	0.99	1.00	1.06
	(0.03)	(0.28)	(0.05)	(0.02)	(0.14)	(0.16)	(0.07)	(0.02)
R^2	0.79	0.28	0.10	0.66	0.71	0.47	0.48	0.49
obs.	102	26	35	141	30	35	40	656

Note: $^{*} p < 0.1$; $^{**} p < 0.05$; $^{***} p < 0.01$

Table 8: Regression results for spread risk.
Source: Authors' calculations.

4.3.2 Loss Absorbing Capacity of Technical Provisions for endogenous losses

Calculations introduced in the previous section can be applied to losses arising after an exogenous shock to asset prices. In the endogenous rounds of iterations (which are iterated until no further losses, see Figure 2), we have to keep track of previous changes in assets and liabilities in order to be able to see whether the threshold $\Delta A_i^{r,SII}$ is breached or not.

There are three possible cases along which we derive the mechanism. Let $R1$ and $R2$ be two consecutive rounds of the simulation procedure, $\Delta A_i^{r,(R1)}$ is the cumulative reduction in asset prices including round $R1$, $\Delta A_i^{r,R2}$ is the new loss arising in round $(R2)$, $\Delta L_i^{r,(R1)}$ and $\Delta L_i^{r,R2}$ are the respective changes in liabilities in the consecutive rounds.

Case 1: $\Delta A_i^{r,R1} < \Delta A_i^{r,SII}$ and $\Delta A_i^{r,R1} + \Delta A_i^{r,R2} < \Delta A_i^{r,SII}$: below threshold in the two rounds
Case 2: $\Delta A_i^{r,R1} < \Delta A_i^{r,SII}$ and $\Delta A_i^{r,R1} + \Delta A_i^{r,R2} > \Delta A_i^{r,SII}$: breaching the threshold in round $R2$
Case 3: $\Delta A_i^{r,R1} > \Delta A_i^{r,SII}$ and $\Delta A_i^{r,R1} + \Delta A_i^{r,R2} > \Delta A_i^{r,SII}$: threshold breached in round $R1$

Case 1: Since $\Delta A_i^{r,R1} + \Delta A_i^{r,R2} < \Delta A_i^{r,SII}$, $(1-\alpha_i^r)\cdot(\Delta A_i^{r,R1} + \Delta A_i^{r,R2}) < (1-\alpha_i^r)\cdot \Delta A_i^{r,SII}$, thus

$$\Delta L_i = \Delta L_i^{r,R1} + \Delta L_i^{r,R2} = (1-\alpha_i^r)\cdot(\Delta A_i^{r,R1} + \Delta A_i^{r,R2}),$$

the adjustment of liabilities in round $R2$ is then:

$$\Delta L_i^{r,R2} = (1-\alpha_i^r)\cdot \Delta A_i^{r,R2}.$$

This case also applies to all risk categories when there is no threshold available (in our simulations for spread risk).

Case 2: To establish the mechanism for this case, assume to be between two rounds $R1$ and $R2$, $\Delta A_i^{r,R1} < \Delta A_i^{r,SII}$ is below the threshold but in R2 cumulative losses breach the threshold, $\Delta A_i^{r,R1} + \Delta A_i^{r,R2} > \Delta A_i^{r,SII}$, as depicted in Figure 4. Below the threshold, the incremental change in liabilities is $\Delta L_i^{r,R1} = (1-\alpha_i^r)\cdot \Delta A_i^{r,R1}$ and this is accounted for in round $R1$. Once this threshold is breached, the total change in liabilities in the current round is:

$$\begin{aligned}\Delta L_i = \Delta L_i^{r,R1} + \Delta L_i^{r,R2} &= (1-\alpha_i^r)\cdot \Delta A_i^{r,SII} \\ &= \underbrace{(1-\alpha_i^r)\cdot \Delta A_i^{r,R1}}_{\Delta L_i^{r,R1}} + \underbrace{(1-\alpha_i^r)\cdot \Delta A_i^{r,SII} - (1-\alpha_i^r)\cdot \Delta A_i^{r,R1}}_{\Delta L_i^{r,R2}},\end{aligned} \tag{10}$$

thus the adjustment of liabilities is

$$\Delta L_i^{r,R2} = (1-\alpha_i^r)\cdot(\Delta A_i^{r,SII} - \Delta A_i^{r,R1})^+ \tag{11}$$

where the positive part is introduced since the change in liabilities in the LAC TP approach cannot be negative, i.e. once aggregate losses on the asset side are above the threshold also in the previous round ($\Delta A_i^{r,SII} < \Delta A_i^{r,R1}$), there is no further adjustment to the liabilities.

Case 3: In this case, the total amount of LAC TP has already been used.
Since $\Delta A_i^{r,SII} < \Delta A_i^{r,R1}$, $\Delta L_i^{r,R2} = (1-\alpha_i^r)\cdot(\Delta A_i^{r,SII} - \Delta A_i^{r,R1})^+ = 0$, the formula is identical to that of the previous case.

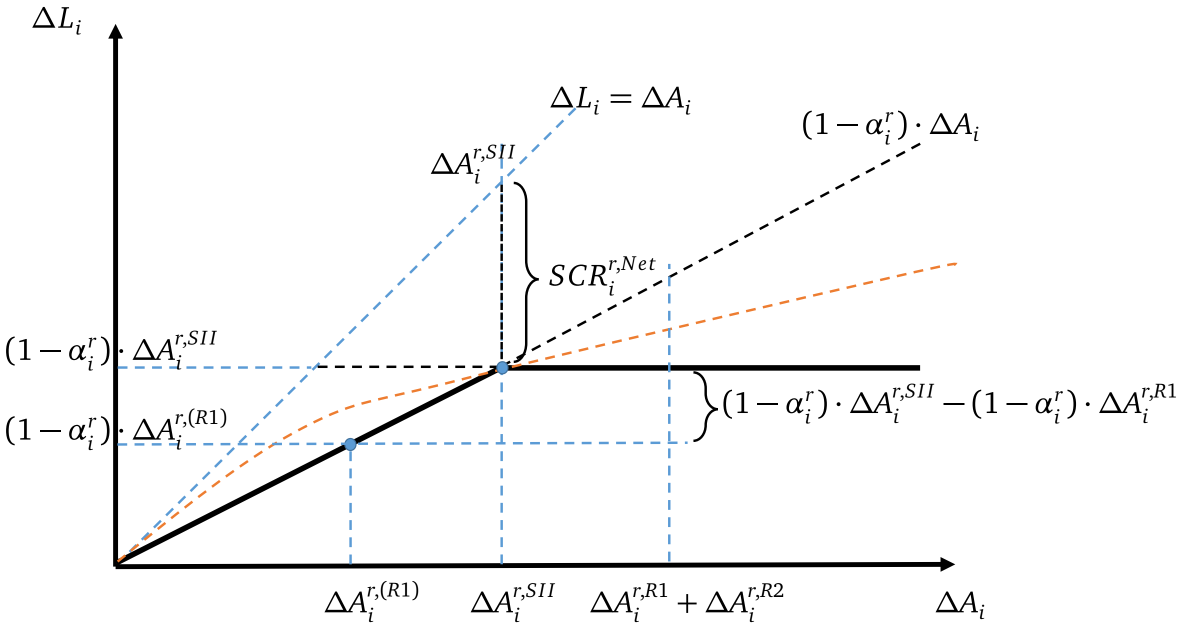

Figure 4: Stylized sketch of the LAC TP approach for an entity i and a two round market risk shock r.

4.3.3 Look-through approach for losses on fund holdings of insurers

Since the LAC TP is reported in the Solvency II framework only for direct equity and bond holdings of insurance undertakings, we also need to derive the LAC TP of insurers for their fund holdings. A special case are insurers offering unit or index linked products. Here the risk of funds held behind these contracts are entirely borne by policyholders. In this process, we apply the so-called look-through approach.[13] We can check the holdings of each fund and derive the share of bond and equity holdings. With this, all funds will be a mixture of bonds and equities. The difficulty comes when funds are holding shares of other funds. An equation system can be established in this case to simultaneously trace the final equity and bond holdings of all funds.

In this section, the following notation is adopted:

- $\mathbf{H}_t^{\text{bnd,f}}, \mathbf{H}_t^{\text{eq,f}} \in \mathbb{R}^{F\times S}$ the matrix of funds' bond and equity holdings, S the total number of securities;
- $\mathbf{H}_t^{\text{fnd,f}} \in \mathbb{R}^{F\times F}$ the matrix of funds' investment fund holdings;
- $\mathbf{H}_t^{\text{fnd,ins}} \in \mathbb{R}^{I\times F}$ the matrix of insurers' investment fund holdings;
- $\mathbf{1}_{\text{bnd}}, \mathbf{1}_{\text{eq}} \in \mathbb{R}^S$ and $\mathbf{1}_{\text{fnd}} \in \mathbb{R}^F$ are column vectors of ones;
- $\mathbf{c}_t \in \mathbb{R}^F$ is the column vector of cash for all funds.

The total asset holdings of a fund i is given by the sum of its bond, equity, fund holdings and cash:

$$a_i = \sum_j h_{i,j}^{\text{bnd, f}} + \sum_j h_{i,j}^{\text{eq, f}} + \sum_j h_{i,j}^{\text{fnd, f}} + c_i, \tag{12}$$

[13] See https://www.eiopa.europa.eu/rulebook/solvency-ii/article-6490_en

where $h^{\text{bnd}}_{i,j} = h_{i,j} \cdot \mathbf{1}(j \text{ is a bond})$. In vector format:

$$\mathbf{a}_t = \mathbf{H}^{\text{bnd,f}}_t \cdot \mathbf{1}_{\text{bnd}} + \mathbf{H}^{\text{eq,f}}_t \cdot \mathbf{1}_{\text{eq}} + \mathbf{H}^{\text{fnd,f}}_t \cdot \mathbf{1}_{\text{fnd}} + \mathbf{c}_t, \tag{13}$$

where $\mathbf{1}_{\text{bnd}}$ and $\mathbf{1}_{\text{fnd}}$ contain 1 or 0 depending on whether the given index of asset is a bond or fund.

We are interested in the amount of bonds in fund i. Let w^{bnd}_i be the share of bonds in fund i. Then, the amount of bonds can be recursively written from equation (12) as

$$w^{\text{bnd}}_i a_i = \sum_j h^{\text{bnd,f}}_{i,j} + \sum_j h^{\text{fnd,f}}_{i,j} w^{\text{bnd}}_j. \tag{14}$$

By dividing by the known amounts a_i, we get

$$w^{\text{b}}_i = \sum_j \frac{h^{\text{bnd,f}}_{i,j}}{a_i} + \sum_j \frac{h^{\text{fnd,f}}_{i,j}}{a_i} w^{\text{b}}_j. \tag{15}$$

Finally, by defining the matrices $\tilde{\mathbf{H}}^{\text{bnd,f}} = \left\{ \frac{h^{\text{bnd,f}}_{i,j}}{a_i} \right\}_{i,j}$ and $\tilde{\mathbf{H}}^{\text{fnd,f}} = \left\{ \frac{h^{\text{fnd,f}}_{i,j}}{a_i} \right\}_{i,j}$, we get to the vector equation

$$\mathbf{w}^{\text{bnd}} = \tilde{\mathbf{H}}^{\text{bnd,f}} \cdot \mathbf{1}_{\text{bnd}} + \tilde{\mathbf{H}}^{\text{fnd,f}} \cdot \mathbf{w}^{\text{bnd}}, \tag{16}$$

from which

$$(\mathbf{I} - \tilde{\mathbf{H}}^{\text{fnd,f}}) \cdot \mathbf{w}^{\text{bnd}} = \tilde{\mathbf{H}}^{\text{bnd,f}} \cdot \mathbf{1}_{\text{bnd}}. \tag{17}$$

The share of bonds for all funds can be easily derived by

$$\mathbf{w}^{\text{bnd}} = (\mathbf{I} - \tilde{\mathbf{H}}^{\text{fnd,f}})^{-1} \cdot (\tilde{\mathbf{H}}^{\text{bnd,f}} \cdot \mathbf{1}_{\text{bnd}}). \tag{18}$$

We show invertibility of matrix $(\mathbf{I} - \tilde{\mathbf{H}}^{\text{fnd,f}})$ in Appendix D.2. Furthermore, due to symmetry, the shares of equities of all funds are

$$\mathbf{w}^{\text{eq}} = (\mathbf{I} - \tilde{\mathbf{H}}^{\text{fnd,f}})^{-1} \cdot (\tilde{\mathbf{H}}^{\text{eq,f}} \cdot \mathbf{1}_{\text{eq}}). \tag{19}$$

By using the previously derived shares, insurers are assigned two parameters, which quantify the share of final equities and the share of final bonds in their fund portfolios. For insurer i

$\frac{\sum_j h^{\text{fnd,ins}}_{i,j} \cdot w^{\text{bnd}}_j}{\sum_j h^{\text{fnd,ins}}_{i,j}} = \frac{\mathbf{H}^{\text{fnd,ins}} \cdot \mathbf{w}^{\text{bnd}}}{\mathbf{H}^{\text{fnd,ins}} \cdot \mathbf{1}_{\text{fnd}}}$ is the share of bonds in fund holdings of insurer i, while

$\frac{\sum_j h^{\text{fnd,ins}}_{i,j} w^{\text{eq}}_j}{\sum_j h^{\text{fnd,ins}}_{i,j}} = \frac{\mathbf{H}^{\text{fnd,ins}} \cdot \mathbf{w}^{\text{eq}}}{\mathbf{H}^{\text{fnd,ins}} \cdot \mathbf{1}_{\text{fnd}}}$ is the share of equities in fund holdings of insurer i.

Thus, when an insurer faces a loss on its fund portfolio, these ratios can be used to calculate the appropriate α^{funds}_i as a weighted average of α^{bonds}_i and $\alpha^{\text{equities}}_i$:

$$\alpha^{\text{funds}}_i = \frac{\sum_j h^{\text{fnd,ins}}_{i,j} \cdot w^{\text{bnd}}_j}{\sum_j h^{\text{fnd,ins}}_{i,j}} \cdot \alpha^{\text{bonds}}_i + \frac{\sum_j h^{\text{fnd,ins}}_{i,j} w^{\text{eq}}_j}{\sum_j h^{\text{fnd,ins}}_{i,j}} \cdot \alpha^{\text{equities}}_i. \tag{20}$$

4.3.4 Modelling the impact from a shock on the risk-free yield curve

Unlike spread and equity shocks, where the LAC TP can be estimated from Solvency II data, variations in the risk-free rate curve (RFR) cause more complex changes in insurers' liabilities. In the first two cases, only the expected cash flow to policyholders is altered, but with changes in the RFR, the discount factor is also impacted. Therefore, the method of calculating LAC TP as proportional to the loss in asset value is no longer applicable. This section explains how we calculate changes in assets and liabilities for shift in the RFR curve, without incorporating LAC TP.

Market shock for bond holdings: Let the yield-to-maturity of a bond be y_{t_M}, where t_M is the term-to-maturity of the bond in years. Then, the price of the bond following the classical linear approximation[14] is derived from

$$\frac{\mathrm{d}p}{\mathrm{d}y_{t_M}} = -D_m \cdot p, \tag{21}$$

where D_m is the modified duration of the bond and $\mathrm{d}y_{t_M}$ is the shift in the yield curve at the corresponding term-to-maturity. Hence, the change in bond price is given by

$$\mathrm{d}p = -D_m \cdot p \cdot \mathrm{d}y_{t_M}. \tag{22}$$

Finally, the new price of the bond given a shock to the corresponding yield curve is

$$p_t = p_{t-1}\left(1 - D_m \cdot \mathrm{d}y_{t_M}\right). \tag{23}$$

Interest rate shock on the liability side: Any change in the RFR changes the discounting rates used to estimate the technical provisions but also the cash flow pattern. Since we do not reproduce sophisticated Solvency II calculations, we adjust the liabilities by deterministic multipliers and based on the concept of effective duration as outlined in (EIOPA, 2016). The calculation is similar to the granular asset side shock calculation above.

The change in liabilities is then

$$\mathrm{d}L = -D_{\mathrm{eff},i} \cdot L_{Base} \cdot \mathrm{d}RFR. \tag{24}$$

where $\mathrm{d}L$ is the change in the discounted best estimate of liabilities, $\mathrm{d}RFR$ is the change in internal rate of return and L_{base} is the starting discounted best estimate of liabilities. For simplicity, we assume the regulatory EIOPA discount curve variation is equal to the swap curve variation used for bond valuation on the asset side. In the implementation, the new amount of liabilities is

$$L_t = L_{t-1} \cdot (1 - D_{\mathrm{eff},i} \cdot \mathrm{d}RFR). \tag{25}$$

For actual country-level effective durations of insurance undertakings, we use the latest publicly available data published by EIOPA which must be used used for RFR and are described in Section 2.3. Table 13 in Appendix D.1 shows the Macaulay and effective durations for all countries in our sample.

Finally, $\mathrm{d}RFR$ is calculated by taking the Macaulay durations of liabilities for country-level insurers, interpreted as the weighted average time-to-maturity. The shock applied is the one on swap rates with the closest maturity to the Macaulay duration. The effective duration is used as a sensitivity measure to interest rate changes.

[14] A more precise approximation could be derived from a second-order estimation using bond convexity.

Aggregate effect of interest rate shock and spread shock: In the chosen scenario, the RFR is reduced, which generally increases bond values, while credit spreads are increased, which generally decreases bond values. Overall, bond values decrease because the negative effect of the increased credit spreads outweighs the positive effect of the reduced RFR. In equation (8), we set ΔA_i^r to the aggregate change in bond values resulting from the RFR and spread shocks. Compared to the alternative of using only the effect of the spread shock for ΔA_i^r, the chosen approach is conservative, since it results in a smaller LAC effect for the reduction in own funds.

5 Results

In the following sections, we present system- and sector-level results of our system-wide stress testing model under the 2021 NGFS hot house world scenario (for details, see Section 3) using the new modelling features described in Section 4.3. These results are then compared to a system with the LAC TP mechanism and the look-through approach for funds holdings of insurers deactivated, to investigate the effect of this deactivation on system losses. This comparison is then further extended with a sensitivity analysis with the application of a market shock multiplier as well as different levels of surrender rates.

5.1 Climate risk in a financial system with insurance companies

The hot house world scenario produces the results shown in Table 9. Aggregate losses amount to roughly 2.29% of total assets of the model's three-sector financial system: market losses dominate, and are approximately three times larger than default losses. Default losses are almost exclusively occurring in response to the exogenous shocks; endogenous reactions only engender minor default losses.

In Appendix E, figure 14 shows how losses evolve until convergence of the algorithm (described in Figure 2). The initial exogenous shocks generate market losses, which amount to half of corresponding default losses but then almost triple in size as the three sectors start interacting. In the next endogenous cycle, these losses start declining to levels more in line with initial default losses, and then quickly become negligible in the following cycles. These findings emphasize the relevance of second-round effects, which represent 60% of the total losses, and are almost exclusively market-driven. Ignoring these effects would lead to a significant underestimation of the magnitude of the losses following this scenario.

Table 9 also shows a breakdown of the sectoral distribution of these losses. While banks suffer the largest default losses (credit risk), funds generate the biggest market losses and are the source of the majority of total system losses. Banks, with their large default losses, generate over 30% of the total, with the insurers' share standing at just under 10%. While insurers are the largest holders of investment fund shares, their second-round market losses are found to be lower than the funds'. As shown in Figure 1, these lower losses can be attributed to the fact that these fund holdings represent only 36% of insurers' total assets, which renders insurers less exposed to market losses than funds.

System- and sector-level results are based on granular, entity-level results. Figure 5 shows losses for each institution as share of each institution's assets, for both the first-round (first row of Figure 5) and second-round effects (second row). The granularity of the results enables the investigation not only of the model's behavior, but also of the agents' reactions to different calibrations, as well as the plausibility of the system reactions to the shocks. A sensitivity analysis to different surrender shocks and market shock magnitudes is discussed in the following sections.

	Defaults	Market
System	0.628%	1.660%
- First-round	0.625%	0.308%
- Second-round	0.003%	1.352%
Banks	0.625%	0.126%
- First-round	0.625%	0.026%
- Second-round	0.001%	0.101%
Funds	0.000%	1.311%
- First-round	0.000%	0.226%
- Second-round	0.000%	1.085%
Insurers	0.002%	0.223%
- First-round	0.000%	0.056%
- Second-round	0.002%	0.166%

Table 9: System- and sector-level losses under the hot house world scenario, as a share of total system assets. The surrender shock is set at 5%.
Note: Sector statistics may not sum up to the system level due to rounding.
Source: Authors' calculations.

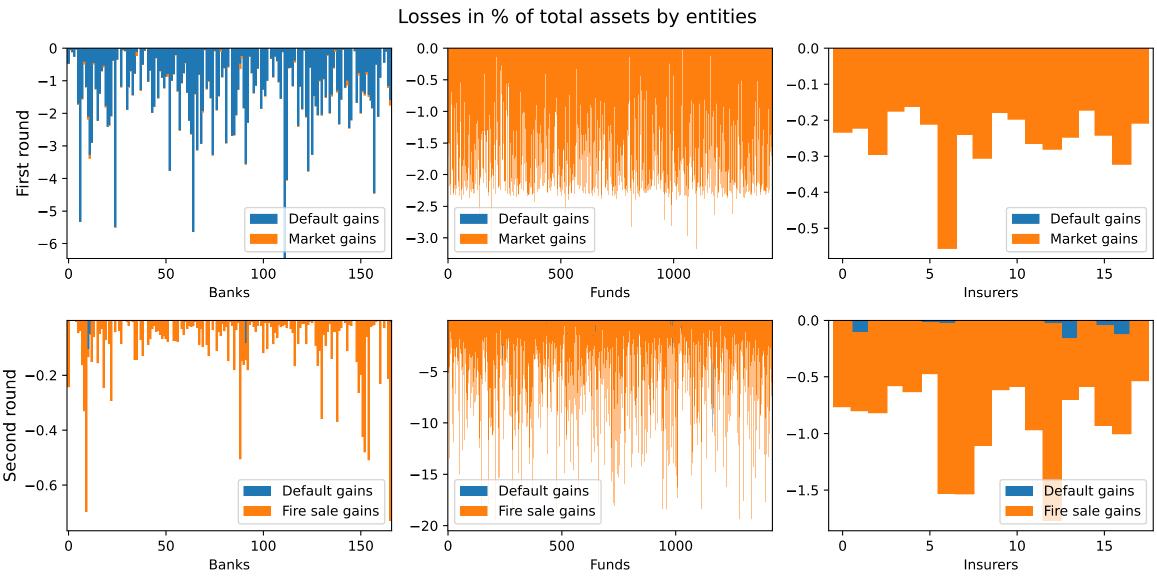

Figure 5: Entities' losses as a share of their assets.
Source: Authors' calculations.

The scenario is insufficiently severe to disrupt the model's country-insurers, which do not experience any liquidity or solvency issue. Insurers' resilience even in the presence of much more severe shocks can be explained by the general business model they operate, but also by the different aggregation level of the insurance sector, which is at the country- and not entity-level as for the other sectors. This feature makes each country-level insurer node in our network much more diversified and able to withstand shocks. In addition to the modelling rationale, the resilience of the sector can be traced back to the profit participation mechanism embedded in life portfolios which allows to partly transfer the impact of the shocks to policyholders. Figure 6 depicts on the left-hand side insurers' total losses on equities, bonds and fund shares, and on the right-hand side the amounts by which these losses are reduced as a result of the model's LAC implementation. Due to the LAC TP mechanism, the adjusted insurer losses in the left panel of Figure 6 amount to just over half of the losses that would not include this mechanism. The LAC TP effect from bonds represents roughly 46% of total LAC TP, followed by fund shares (31%), and lastly, equities (23%).

Liquidity outflows are a major source of fire sale losses in the second-round reactions of the model. Figures 7-8 show these results for funds, insurers and banks, respectively. Values are displayed in percentages of individual entities' assets, which enables the identification of institutions that are riskier than others. In Figure 7, initial fund redemptions are derived from the assumed flow-performance relationship coefficients (Section 3.3) as a function of the individual funds' price reaction after the initial market shock. Using the climate market shock, initial outflows for corporate bond funds are found to be larger than for all other fund categories, although quite limited. The right panel shows second-round fund redemptions, which are the results of all entities' closing their liquidity gaps. Insurers' initial outflows, depicted in Figure 8, are the highest of all sectors in this simulation due to the assumed 5% surrender shock on the surrender values; these outflows also lead to pronounced insurers' fund redemptions and sales of assets.

Figure 9 shows second-round fund redemptions and NAV drops of funds. Equity fund outflows are found to be higher, as a result of their shares in insurers' balance sheets. All funds react to outflows by selling their securities and redeeming other funds' shares. With second-round fund redemptions equity funds suffer larger outflows, which prompt these funds to react by selling equities more than other funds, which in turn leads to higher price reactions of equities (right panel of Figure 9). The impact on sovereign bonds is negligible, since the climate scenario assumes no impact on sovereigns and their share in the whole investment fund sector is also small.

The right panel of Figure 8 shows the net interbank flows in the banking system. These flows emerge following banks'credit risk losses, which pushes some banks into solvency distress. It is assumed that distressed or defaulted banks start withdrawing short-term funding from all other bank counterparties, while all other banks having distressed or defaulted counterparties also withdraw short-term funding from these counterparties. This may lead to liquidity shortfalls of banks, measured as a deviation from an HQLA level of 100% for the LCR. Overall, these withdrawals are able to close the liquidity gaps of banks and do not lead to further fire sales of securities.

5.2 The mitigating role of insurance companies

In order to investigate the LAC TP's loss-reduction ability, the model is also run with an inactive LAC TP mechanism, which includes the related look-through approach for losses on fund holdings of insurers (in short 'LAC TP mechanism'). Given that the climate scenario leads to small system losses due to the mild market shock, we apply a multiplier to the climate risk market shocks.

While not fully consistent with a scenario based on a climate change narrative, we also extend the scope of the sensitivity analysis to the surrender shock for insurance undertakings, by considering surrender shocks in the range 0 to 10%. Figures 10 and 11 display the difference between

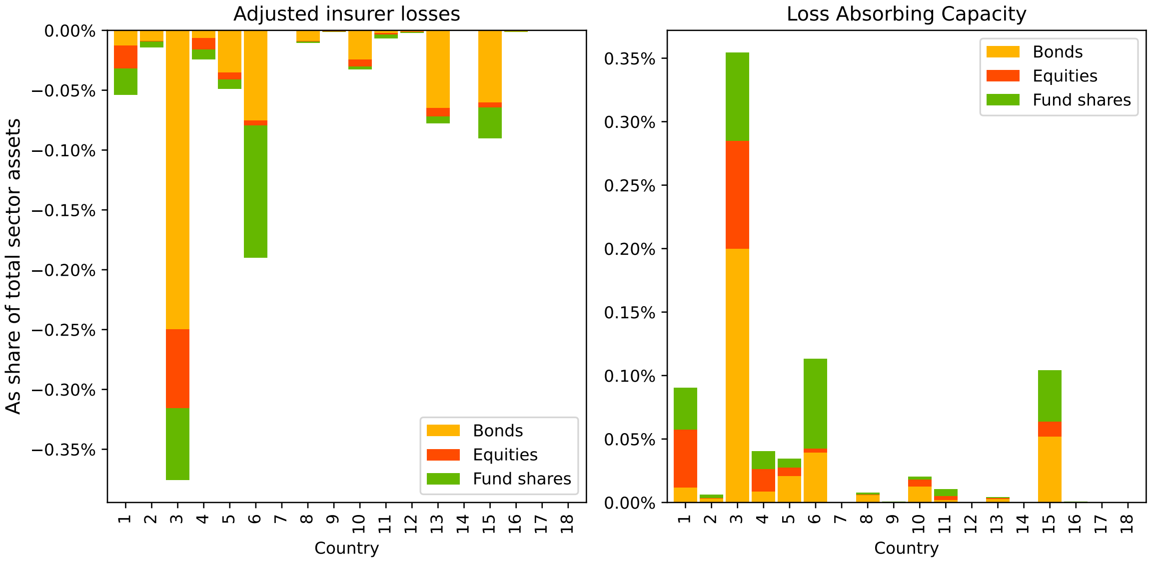

Figure 6: Adjusted insurers' losses in % of the insurance sector's total assets and LAC loss reduction for all asset types.
Source: Authors' calculations.

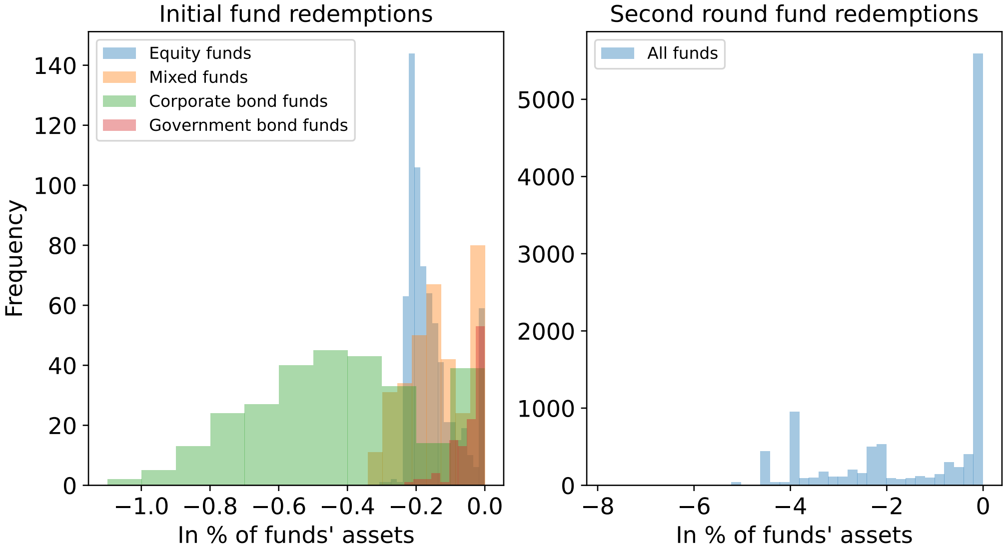

Figure 7: Distribution of outflows from investment funds.
Source: Authors' calculations.

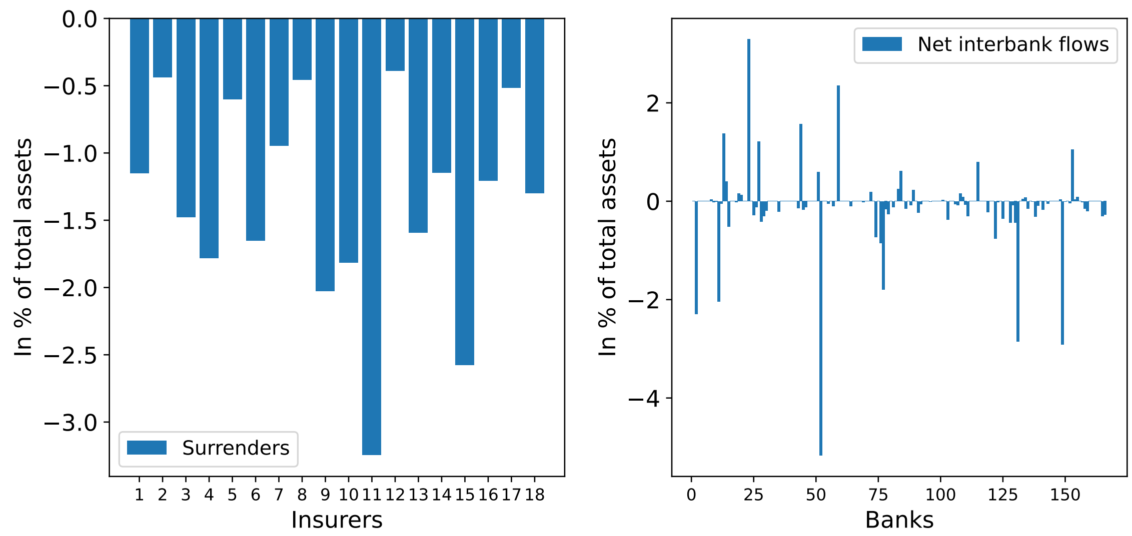

Figure 8: Outflows from banks and insurers, in % of entities' total assets.
Source: Authors' calculations.

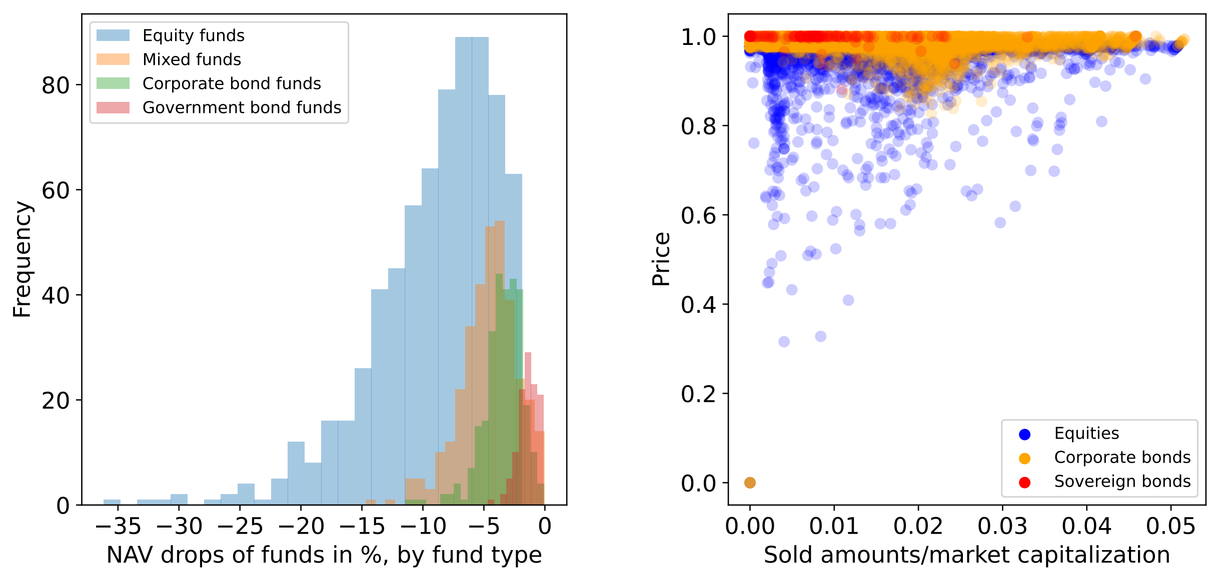

Figure 9: Distributions of fund price drops and equilibrium prices of securities as functions of sold amounts.
Source: Authors' calculations.

losses generated by a system with the LAC TP mechanism active and a system with this mechanism deactivated.[15] Negative values reflect the fact that the deactivation of LAC TP generates overall larger losses.

While LAC TP has by design also an immediate effect on insurers' losses, the loss-reduction ability of this mechanism compounds and becomes more prominent in later iterations; this compounding, however, does not result in a decrease of the number of default and distress events. This result is a consequence of the fact that the climate scenario is too mild to push any entity into a default state.

Overall, the inclusion of this mechanism results in a decline of 7.62% of total system losses and disproportionately affects second-round losses for the insurance sector.[16]

	Round	
	First	**Second**
System	-4.98%	-9.34%
Banks	0.00%	0.00%
Funds	0.00%	0.00%
Insurers	-46.47%	-45.31%

Table 10: System- and sector-level decline in losses due to LAC TP under the 2050 hot house world scenario (in percentage). Bank and fund loss reductions are too small to show.
Source: Authors' calculations.

A breakdown of the loss decline for the total system due to the introduction of LAC is summarised in Table 10. The first-round loss decline for banks and funds amounts to zero due to the LAC TP having a direct effect only on insurers. A 46% and a 45% first- and second-round loss decline for insurers results in a lower decline at the system level (5% and 9%, respectively, for first-round and second-round system losses), reflecting the different magnitude of sectoral losses described in earlier sections and the negligible loss reductions for banks and funds.

The effect of the LAC TP mechanism on market losses is in full display in Figures 10 and 11. The market shock multiplier generates a shock which is up to ten times larger than the original climate market shock, while the surrender shock for all insurers can be as high as 10% of the surrender values. In addition, a euro area swap shock of up to -50 basis points (see section **??**) is assumed in order to generate a default in the insurance sector in an extreme scenario.

Figure 10 shows the impact of LAC TP on system-level total losses. The average loss reduction across all simulation considered in the sensitivity analysis is around 11%, with reductions ranging from 5% for the simulation with no surrender shock and the base market shock to around 20%, for the simulation with no surrender shock and a ten-fold market shock multiplier.

The LAC TP's impact is rather limited for first-round losses (just above 11%) even when the market shock is amplified ten-fold. The loss reduction increases with higher market shocks, and different calibrations for the surrender shock have no effect on system loss reductions; this finding is explained by the fact that insurers' losses do not have a direct impact on the other sectors in first-round losses since there is no reaction of the entities.

[15] The same results are shown in Table 10, using the hot house world scenario.

[16] Loss reduction due to LAC is dominated by second-round losses, which represent 73% of this reduction. The insurance sector experiences almost exclusively the loss reduction: in a system with LAC, insurers' losses decline by almost 46%, with negligible bank and fund loss declines. These figures are slightly different from those of Table 10 in that they aggregate market and default losses.

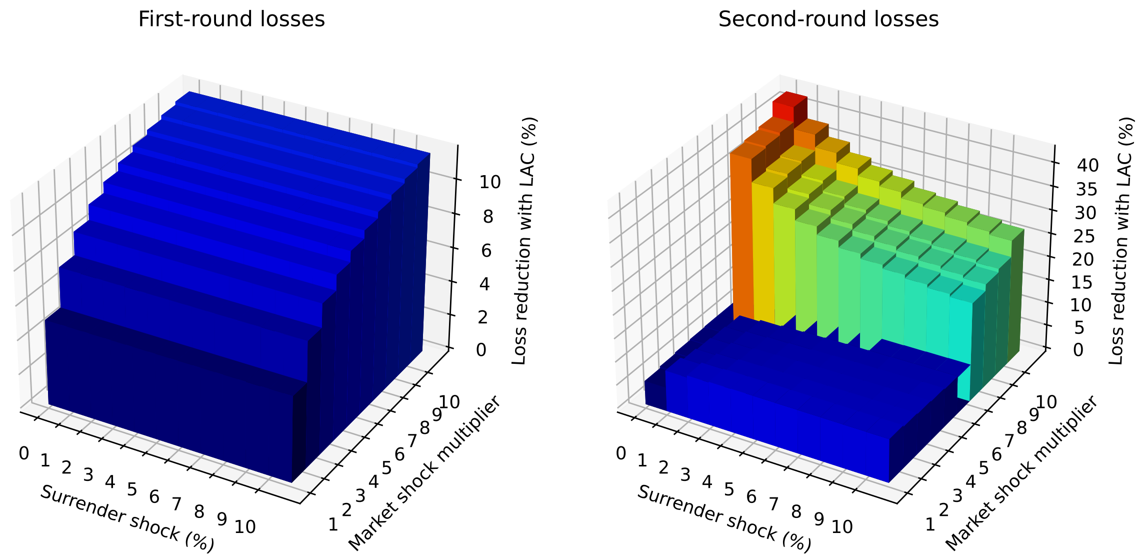

Figure 10: Reduction in total losses for the entire system due to LAC TP, across a range of sensitivity parameters.
Source: Authors' calculations.

Different conclusions can be drawn for second-round system-level losses. The impact of LAC is quite contained insofar the market shock is limited. The inclusion of the smallest surrender shock (1%) increases second-round system loss reduction by almost four percentage points. However, once the market shock becomes strong enough for one or more insurers to default, the loss reduction spikes. These spikes are evident in Figure 10, where in correspondence to a market shock multiplier of seven to ten, second-round losses are observably higher. In these simulations, one or more insurers default, their portfolios are liquidated, which in turn negatively impact asset prices for all sectors. As these prices decline, an increasing number of funds suffer losses, further increasing system losses. These defaults, however, are prevented thanks to the LAC TP mechanism, which generates the large loss reductions.

When one or more solo insurance undertakings default is triggered, bigger surrender shocks have instead a dampening effect on the loss reduction; this can be explained by the fact that this shock is able to introduce losses into the system which appear also when LAC TP is deactivated. The highest loss reduction (-43%) is associated with no surrender shock and the strongest market shock considered.

Appendix Figures 15 and 16 show that, consistently with Table 10, there is no impact of LAC TP (represented by a blue, flat panel) on first-round market losses for both banks and funds. Second-round losses for these institutions broadly resemble the loss distribution seen at the system level in Figure 10.

In Figure 11, first-round loss reductions for insurers also emerge as expected, and are level across all simulations. As the stronger market shocks trigger insurers' and funds defaults, second-round loss reductions spike; these spikes are much less evident for insurers than at the system level, since insurers experience relatively larger second-round market loss reductions due to LAC TP even with no or small surrender and market shocks. It is this large reduction that saturates the LAC TP's and surrender shocks' loss reduction capacity.

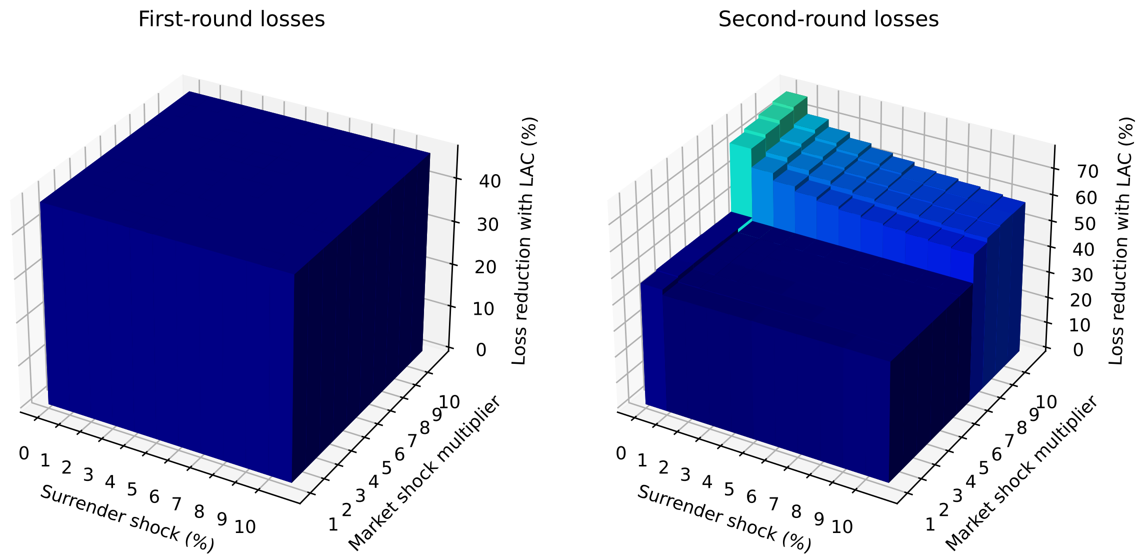

Figure 11: Reduction in total losses for insurers due to LAC TP, across a range of sensitivity parameters.
Source: Authors' calculations.

6 Conclusion

This paper discusses how the two-sector stress testing framework, covering a network of banks and funds as documented in Sydow et al. (2024), is further extended to include another non-bank financial institution (NBFI) sector, here the insurance sector.

The framework is enhanced in its insurance modelling component, which now proposes a full balance sheet approach based on the duration of assets, effective duration of liabilities and the thereof dynamics. Additionally, the model estimates the capacity of technical provisions to absorb losses from the devaluation of equities and bonds. This enhancement allows capturing in the estimation of the liabilities the profit participation mechanism embedded in specific life portfolios, which allows to transfer part of the market risks to policyholders.

For an illustration of the model capabilities, we examine a hypothetical NGFS's 'hot house world' macro-financial shock scenario, incorporating an additional, not scenario-related surrender shock for insurers and shock multipliers for sensitivity analysis. Under this scenario, we find that an interconnected financial system of banks, funds and insurers amplifies initial macro-financial shocks, despite the mild shocks introduced to the system. By considering multiple connected risk channels, sizable second-round amplification effects are discovered, which are noteworthy in all three sectors: portfolio overlaps and cross-holdings of fund shares and securities are the main sources of second-round losses. Insurers are the major drivers of fund redemptions due to their large fund shares holdings. Additionally, within the limitations of the model, results show that risk transfer dynamics embedded in with-profit insurance liabilities helps to reduce losses for the insurance sector and the entire system.

These findings not only advocate the employment of system-wide stress tests as scenario-based analytical tools, but also the further improvement of the modelling of insurers' LAC TP mechanisms for a more realistic stress test result.

This model is currently being expanded to cover additional channels of liquidity distress, such as bank deposit outflows as well as endogenous margin calls. Looking forward, the model could be used to investigate the impact of liquidity or monetary policy shocks, but it could also be employed to investigate the effect of additional capital buffer requirements or fund-level redemption restrictions.

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A Mathematical and balance sheet notations

A.1 Mathematical notations

Variable	Definition
a	Real number
$\mathbf{a} = \{a_i\}_{i \in \mathcal{I}}$	Vector of real numbers
$\mathbf{A} = \left\{a_{i,j}\right\}_{i \in \mathcal{I}, j \in \mathcal{J}}$	Matrix of real numbers, where $\mathcal{I}$ and $\mathcal{J}$ are index sets of integers
$\frac{\mathbf{a}}{\mathbf{b}} = \left\{\frac{a_i}{b_i}\right\}_{i \in \mathcal{I}}$; similarly, $\frac{1}{\mathbf{b}} = \left\{\frac{1}{b_i}\right\}_{i \in \mathcal{I}}$	Fraction of two vectors, to be interpreted as element-wise division
Superscript $\cdot^{\mathrm{T}}$	Transpose of a matrix or vector
$\mathbf{c} = \mathbf{A} \cdot \mathbf{b} = \left\{\sum_{j \in \mathcal{J}} a_{i,j} b_j\right\}_{i \in \mathcal{I}} = \{c_i\}_{i \in \mathcal{I}}$	Product of a matrix $\mathbf{A}$ and a column vector $\mathbf{b}$ resulting in a vector $\mathbf{c}$, denoted following the mathematical standards
$\mathbf{A}^{-1}$	Inverse of a matrix $\mathbf{A}$, given $\mathbf{A}$ and $\mathbf{b}$, it solves $\mathbf{Ax} = \mathbf{b}$ for $\mathbf{x}$ as $\mathbf{x} = \mathbf{A}^{-1}\mathbf{b}$
$\mathbf{A}\mathbf{b}^{\mathrm{T}} = \left\{a_{i,j} b_j\right\}$	Product of a matrix $\mathbf{A}$ and a row vector $\mathbf{b}^{\mathrm{T}}$,in other words, column j of the matrix is multiplied by b_j
$\mathbf{1}$	Column vector of ones
$\mathbf{A} \cdot \mathbf{1} = \sum_j a_{i,j}$	Sum of the rows of the matrix
$\mathbf{A}^{\mathrm{T}} \cdot \mathbf{1}$	Sum of the columns of the matrix
t	Time dimension, it has no clear measurable interpretation in our model and it only indicates that $t+1$ is taking place after t
b_t	State of b in time t, when it is not necessary, we do not use the index t
W_t	Random variables, denoted by capital letters with time indices
$\mathbf{W}_t$	Vector of random variables

Table 11: Mathematical notations

A.2 Common balance sheet notations

Banks, funds and insurers hold securities on their asset side and have these securities also on their liability side as issued securities. Securities are aggregated to the issuer and asset type (equity or bond) level. Open-end investment fund holdings are redeemable assets, bonds and equities are

Variable	Definition
$\mathbf{H} = \{h_{i,j}\}$	Matrix of all securities holdings
$h_{i,j}$	Securities issued by j held on i's balance sheet
$\sum_j h_{i,j}$	Amount of securities held by i
$\sum_j h_{j,i}$	Amount of securities issued by i
$h_{i,\phi}$	A security holding of entity i of a specific security ϕ
$\mathbf{H}^{\text{fnd}}$	Fund holdings matrix ($\{h_{i,\phi}\}$, where ϕ are funds)
$\mathbf{H}^{\text{bnd}}$	Bond holdings matrix
$\mathbf{H}^{\text{eq}}$	Equity holdings matrix
$l_{i,j}$	Loans from bank i to an entity j from any sector
$\sum_j l_{i,j}$	Amount of loans of bank i
$\sum_j l_{j,i}$	Sum of the debt of entity i, a liability of i
c_i or $\mathbf{c}$	Amount of cash or liquid buffer for entity i or when stacked into a vector for all entities
k_i or $\mathbf{k}$	Amount of capital items for entity i or in vector notation
τ_i^{def}, τ_i^{dis}	Solvency default and distress thresholds for entity i
$\tau_i^{c,\text{def}}$, $\tau_i^{c,\text{dis}}$	Liquidity distress and default thresholds for entity i
if $c_i < \tau_i^{c,\text{dis}}$	Entity i is in liquidity distress
if $c_i < \tau_i^{c,\text{def}}$	Entity i is in liquidity default
if $k_i < \tau_i^{\text{dis}}$	Entity i is in solvency distress
if $k_i < \tau_i^{\text{def}}$	Entity i is in solvency default

Table 12: Common balance sheet notations

tradable assets. Holdings are indexed by issuers in the paper, but the model keeps track of their evolution at asset type level also: equity or bond. Only if necessary, we will denote a security holding of a given entity of a specific security. For banks, we assume that tradable assets only consist of assets that are not eligible for central bank operations. On the other hand, funds and insurers can sell all kinds of assets as they do not have access to any central bank facilities. Another considered balance sheet item is the amount of cash (for funds and insurers) or liquid buffer which for banks are the amount of high-quality liquid assets (HQLA), assumed to be cash-equivalent (in result of central bank operations). Furthermore, a bank has a portfolio of loans on its asset side. Interbank loans also appear as liabilities of debtor banks, but investment funds and insurers can also have loans as liabilities, representing the sum of their debt. Depending on the respective financial sector, solvency and liquidity default and distress thresholds are defined, see Appendix C.

B Visualization of exposure networks

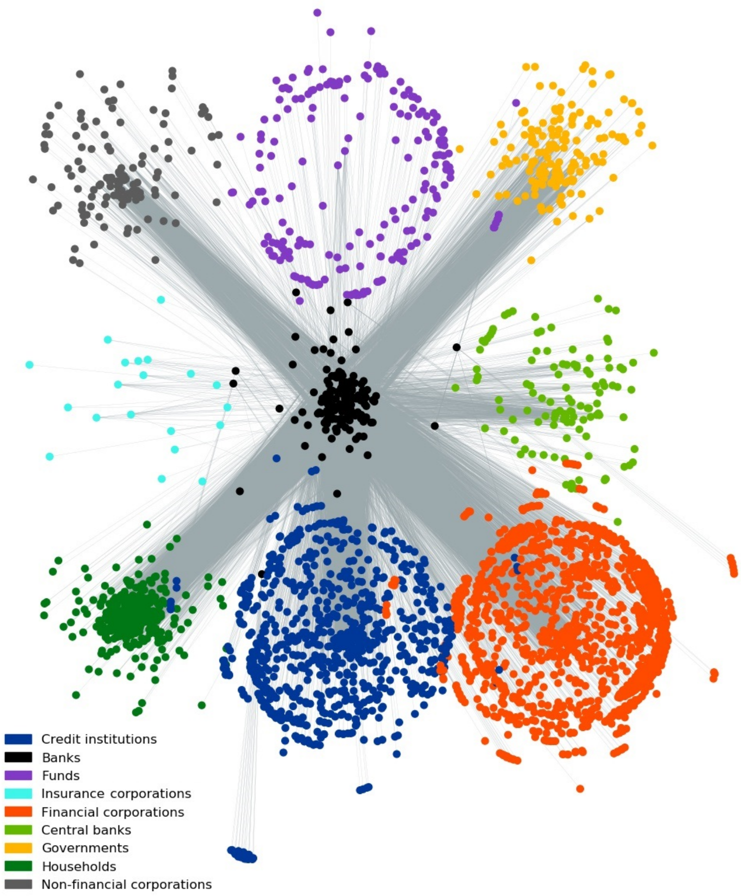

Figure 12: Loans exposure networks from banks to all sectors at entity level in Q4 2020. Source: Authors' calculations.

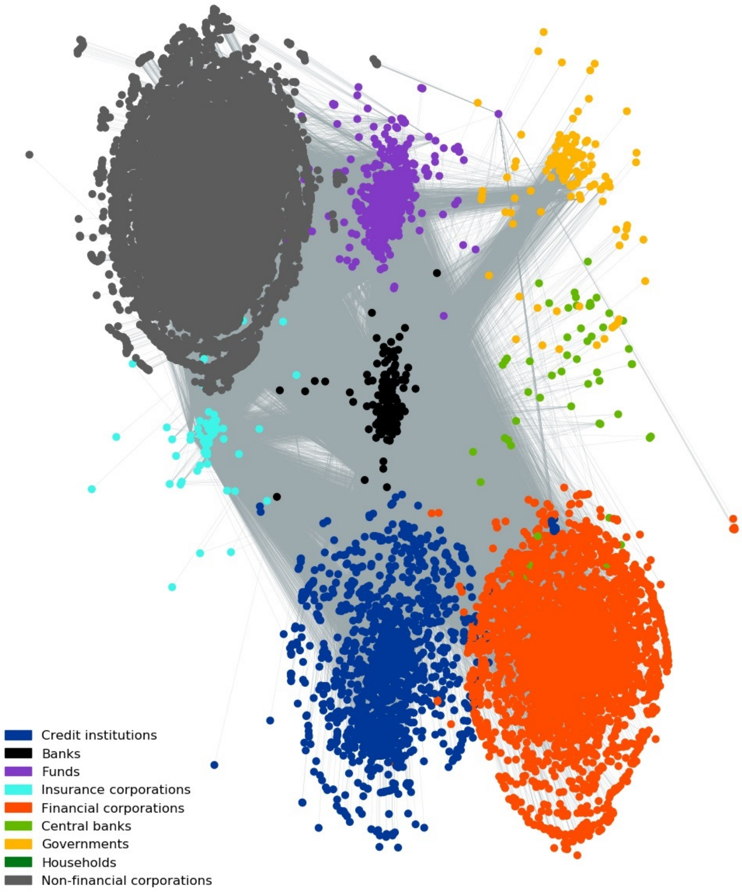

Figure 13: Portfolio holding connections at entity level in Q4 2020. An edge represents that a bank/fund/insurer holds assets issued by another entity of a sector.
Source: Authors' calculations.

C Regulatory constraints

C.1 Banking sector regulatory constraints

Solvency capital requirements: We account for two solvency thresholds for each bank i: a distress threshold τ_i^{dis} and a lower default threshold τ_i^{def}. The uniform minimum CET1 capital requirement is $\chi^{\text{MC}} = 4.5\%$. On top of this, bank-specific Pillar 2 requirements χ^{P2R} are added, determined by the Supervisory Review and Evaluation Process (SREP) and the shortfall of additional Tier-1 and Tier-2 capital $\chi^{\text{sf AT1/T2}}$, which are also part of the CET1 requirements from 2020 onwards[17], hence the default threshold in percentages is

$$\chi^{\text{def}} = \chi^{\text{MC}} + \chi^{\text{P2R}} + \chi^{\text{sf AT1/T2}}.$$

For the distress threshold, we add the combined buffer requirement (CBR), which is the sum of the uniform capital conservation buffer (CCoB), the counter-cyclical capital buffer (CCyB) and the maximum of the structural risk related macroprudential capital requirements: systemic risk buffer (SyRB), buffer for global systemically important institutions (G-SII) and buffer for other

[17]For more information see the 2020 SSM SREP Methodology Booklet.

systemically important institutions (O-SII):

$$\chi^{\mathrm{CBR}} = \chi^{\mathrm{CCOB}} + \chi^{\mathrm{CCyB}} + \max\{\chi^{\mathrm{SyRB}}, \chi^{\mathrm{O-SII}}, \chi^{\mathrm{G-SII}}\}.$$

The distress threshold is then given by

$$\chi^{\mathrm{dis}} = \chi^{\mathrm{def}} + \chi^{\mathrm{CBR}}.$$

The default and distress thresholds in monetary units are obtained for each bank i by multiplying capital requirements by the total risk exposure amount (REA):

$$\tau_i^{\mathrm{def}} = \chi^{\mathrm{def}} \cdot \mathrm{REA}_i, \quad \tau_i^{\mathrm{dis}} = \chi^{\mathrm{dis}} \cdot \mathrm{REA}_i \; . \tag{26}$$

Liquidity regulation: We take into account the LCR constraint, designed to increase the short-term resilience to liquidity shocks. It does so by requiring banks to hold an adequate stock of unencumbered High Quality Liquid Assets (HQLA) to meet their liquidity needs for a 30-calendar-day liquidity stress scenario. We denote this as

$$\mathrm{LCR}_i = \frac{c_i^{\mathrm{HQLA}}}{c_i^{\mathrm{out}\ 30}} \geq 1, \tag{27}$$

where c_i^{HQLA} denotes the stock of HQLA and $c_i^{\mathrm{out}\ 30}$ is the net cash outflows over the next 30 calendar days under a stress scenario.

While minimum capital requirements must always be satisfied, it is accepted for the LCR to fall below 100% during crisis times (Basel Committee on Banking Supervision, 2020), although it may entail additional supervisory activities. However, in this work we use the parameter $\lambda^{\mathrm{LCR}} = 1$, which determines the portion of LCR that banks actually try to maintain during stress periods, i.e. they make sure that $c_i^{\mathrm{HQLA}} \geq \lambda^{\mathrm{LCR}} \cdot c_i^{\mathrm{out}\ 30}$. The liquidity distress threshold is

$$\tau_i^{c,\mathrm{dis}} = \lambda^{\mathrm{LCR}} \cdot c_i^{\mathrm{out}\ 30}. \tag{28}$$

The liquidity default threshold is $\tau_i^{c,\mathrm{def}} = 0$. The pool of HQLA as cash-equivalent liquidity for bank i is c_i. This assumes that banks have access to central bank repo financing and that they are able to exchange their liquid assets into cash within a short time horizon.

C.2 Investment fund sector constraints

Funds are modelled to default when their NAV reaches zero. We synthetically define the total net assets (TNA) of a fund i as a capital-like measure resembling the difference of financial assets and liabilities to banks

$$k_i = \sum_j h_{i,j}^{\mathrm{fnd}} + \sum_j h_{i,j}^{\mathrm{bnd}} + \sum_j h_{i,j}^{\mathrm{eq}} + c_i - \sum_j l_{j,i}. \tag{29}$$

In this sense, we are able to identify funds that are in solvency default, i.e. using a default threshold $\tau_i^{\mathrm{def}} = 0$:

$$k_i < 0 = \tau_i^{\mathrm{def}}. \tag{30}$$

The liquidity default threshold is similarly given by $\tau_i^{c,\mathrm{def}} = 0$, leading to the liquidity default condition

$$c_i < 0 = \tau_i^{c,\text{def}}, \tag{31}$$

where c_i denotes cash of investment funds. Note that this difference compared to banks does not cause ambiguity, because funds with cash shortage will sell their tradable assets or redeem other fund shares to obtain liquidity. Also, note that distress thresholds are defined for the investment fund sector given the absence of related regulation. Furthermore, since funds are able to convert their assets into cash, a liquidity-induced default would not be triggered in our model. A liquidity default would only occur if funds have sold all of their assets; however, this is clearly preceded by a solvency default, as shown in equation (29) and in the solvency default condition $k_i < 0$. Finally, fund defaults appear very unlikely as the value of their assets is far higher than the loans on their liabilities.

Under UCITS III, leverage can be used for investment purposes, with no need to match specific assets, but it is limited.[18] On the other hand, the Alternative Investment Fund Managers (AIFM) directive does not include leverage limits, but corresponding funds are usually only moderately leveraged, with the exception of hedge funds.[19] Therefore, investment funds modelled in our framework exhibit a low leverage.

C.3 Insurance sector constraints

Insurance companies are modelled to meet the SCR regulation requirements laid down in the Solvency II regulation. More specifically, insurers' own funds must be above the Solvency Capital Requirement (SCR) and the Minimum Capital Requirement (MCR).

An insurer becomes distressed if

$$k_i < \tau_i^{\text{dis}}, \tag{32}$$

where τ_i^{dis} (solvency distress threshold) is the SCR. An insurer defaults if

$$k_i < \tau_i^{\text{def}}, \tag{33}$$

where τ_i^{def} (solvency default threshold) is the MCR. No liquidity requirements are prescribed for insurance companies.

D Insurance modelling details

D.1 Insurance sector: LAC regressions and data

LAC regressions Estimations of $\beta_0^{r,country}$, $\beta_{Life}^{r,country}$ and $\beta_{UL}^{r,country}$ are carried out for each risk category r by regressing:
Type 1 equities

$$\alpha_i^{type1} = \frac{S.26.01.04, R0210, C0060}{(S.26.01.04, R0210, C0020) - (S.26.01.04, R0210, C0040)} \tag{34}$$

[18] Funds can borrow up to 10% of their net asset value (NAV) on a temporary basis (financial leverage).While it is not allowed to short stocks, the same can be achieved using derivatives, up to 100% NAV (synthetic leverage). However, this form of leverage is also constrained directly or indirectly under the UCITS Directive.

[19] For more details, see ESMA (2019).

and spread risk (bonds and loans)

$$\alpha_i^{Spread} = \frac{S.26.01.04, R0410, C0060}{(S.26.01.04, R0410, C0020) - (S.26.01.04, R0410, C0040)} \tag{35}$$

on technical provisions aggregates for each insurance group i

$$\text{Life}_i = \frac{\text{TP Life (excluding UL)}}{\text{Total Assets}} = \frac{S.02.01.01, R0650, C0010}{S.02.01.01, R0500, C0010} \tag{36}$$

$$\text{UL}_i = \frac{\text{TP Unit Linked}}{\text{Total Assets}} = \frac{S.02.01.01, R0690, C0010}{(S.02.01.01, R0500, C0010} \tag{37}$$

using confidential Solvency II data. α_i^r, Life_i and UL_i only assume values in the interval [0,1].

Insurance data Durations and data items from Solvency II templates

	Duration of TP life for all lines of business	
	Approx. effective duration	Macaulay duration (liabilities)
AT	9.96	15.77
BE	7.65	10.99
BG	15.44	15.33
CY	4.55	8.03
CZ	5.01	9.46
DE	8.67	21.40
DK	16.73	17.59
EE	2.85	11.36
ES	10.89	10.10
FI	5.76	12.40
FR	4.55	13.36
GR	10.03	9.78
HR	7.36	9.31
HU	2.39	8.38
IE	12.27	10.83
IT	4.46	9.49
LI	N/A	8.59
LT	11.69	14.02
LU	2.38	11.78
NL	14.67	16.40
NO	4.17	15.51
PL	7.08	10.67
PT	4.47	5.23
RO	5.06	11.71
SE	18.55	16.57
SI	8.71	13.17
SK	N/A	11.33
UK	4.59	10.57
EU/EEA	8.23	13.97

Table 13: Macaulay and effective durations.
Source: EIOPA (2016).

Country	Exposure rate (life): EXP^{life}	Lapse impact (life)	Exposure rate (UL): EXP^{UL}	Lapse impact (UL)
AT	7%	1%	53%	1%
BE	58%	2%	31%	0%
CY	93%	93%	3%	-1%
CZ	49%	11%	46%	-1%
DE	71%	1%	67%	1%
DK	17%	39%	89%	49%
ES	52%	0%	62%	-13%
FI	67%	57%	98%	61%
FR	34%	2%	76%	3%
GR	47%	1%	54%	26%
HR	74%	51%	57%	57%
HU	83%	19%	81%	3%
IE			30%	-8%
IT	61%	3%	89%	31%
LI			98%	81%
NL	11%	0%	35%	0%
NO	75%	20%		
PL	97%	41%	78%	19%
PT	25%	1%	-10%	-11%
RO	83%	59%	11%	0%
SE	61%	4%	57%	1%
SI	31%	22%	82%	21%
SK	76%	22%	65%	28%

Table 14: Mass lapse exposure rates and impacts per jurisdiction and line of business
Life - Insurance with profit participation, UL - Index-linked and unit-linked insurance
Where values are missing, European average is used.
Source: EIOPA (2019), Annex 1.

Variable	Template	Row	Column	Item
	Balance sheet			
c_i	S.02.01.01.01	R0410	C0010	Cash and cash equivalents
A_i	S.02.01.01.01	R0500	C0010	Total Assets
L_i				Technical provisions:
TP_i^{life}	S.02.01.01.01	R0650	C0010	Life (excluding health and index-linked and unit-linked)
TP_i^{UL}	S.02.01.01.01	R0690	C0010	Index-linked and unit-linked
	Own funds			
k_i				Total eligible own funds:
	S.23.01.01.01	R0540	C0010	to meet the SCR
	S.23.01.01.01	R0550	C0010	to meet the MCR
τ_i^{dis}	S.23.01.01.01	R0580	C0010	SCR
τ_i^{def}	S.23.01.01.01	R0600	C0010	MCR
	Solvency Capital Requirement - Market Risk			
$A_{i-1}^{r,SII}$				Initial absolute values before shock, Assets:
	S.26.01.04.01	R0210	C0020	Equity risk type 1 equities
	S.26.01.04.01	R0410	C0020	Spread risk bonds and loans
$A_i^{r,SII}$				Absolute values after shock, Assets:
	S.26.01.04.01	R0210	C0040	Equity risk type 1 equities
	S.26.01.04.01	R0410	C0040	Spread risk bonds and loans
$SCR_i^{r,Net}$				Absolute values after shock, Net Solvency Capital Requirement:
	S.26.01.04.02	R0210	C0060	Equity risk type 1 equities
	S.26.01.04.02	R0410	C0060	Spread risk bonds and loans

Table 15: Solvency II data and variables used in the modelling of the insurance sector.

D.2 Proof for look-through matrix invertibility

We show the invertibility of matrix in equation (19). For this, we use the Neumann series representation of $(\mathbf{I}-\tilde{\mathbf{H}}^{\text{fnd,f}})^{-1}$:

$$(\mathbf{I}-\tilde{\mathbf{H}}^{\text{fnd,f}})^{-1} = \sum_{k=0}^{\infty}(\tilde{\mathbf{H}}^{\text{fnd,f}})^{k}. \tag{38}$$

If we can show that the norm of $\tilde{\mathbf{H}}^{\text{fnd,f}}$ is smaller than one in any norm, then the sum above converges and the inverse exists.

By choosing the ∞-norm,

$$\left\|\tilde{\mathbf{H}}^{\text{fnd,f}}\right\|_{\infty} = \max_{i}\sum_{j}\left|\frac{h_{i,j}^{\text{fnd,f}}}{a_i}\right| = \max_{i}\frac{\sum_j h_{i,j}^{\text{fnd,f}}}{a_i} < 1,$$

is a consequence, since an individual fund holding of fund i cannot be larger than the total assets of fund i as the definition in equation (12) confirms it. □

E Further results

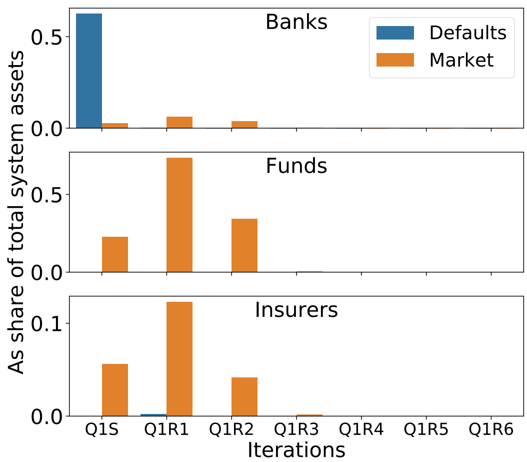

Figure 14: Total sector-level losses under the hot house world scenario
Source: Authors' calculations.

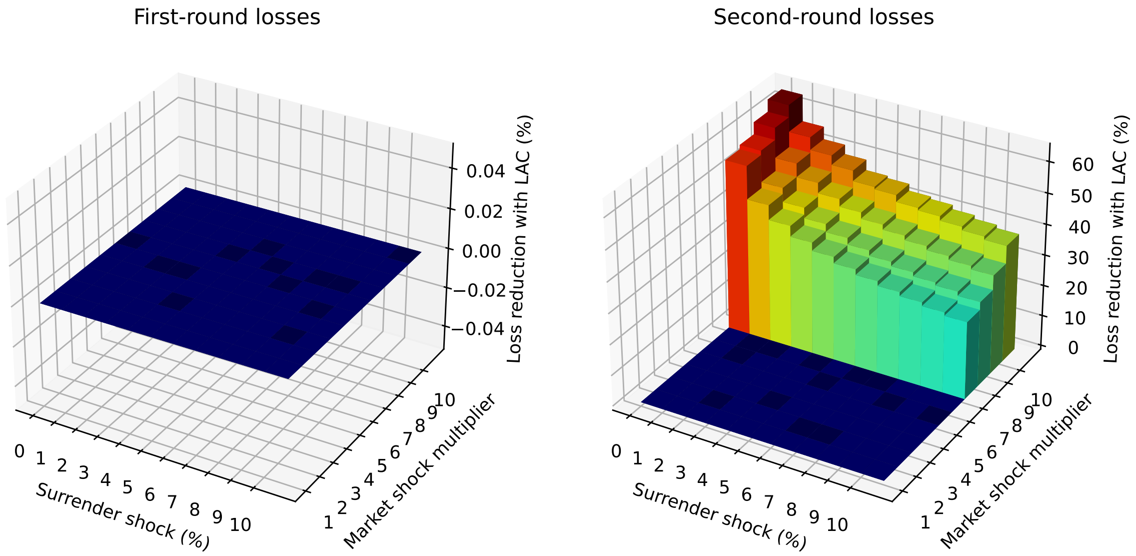

Figure 15: Reduction in market losses for banks due to LAC.
Source: Authors' calculations.

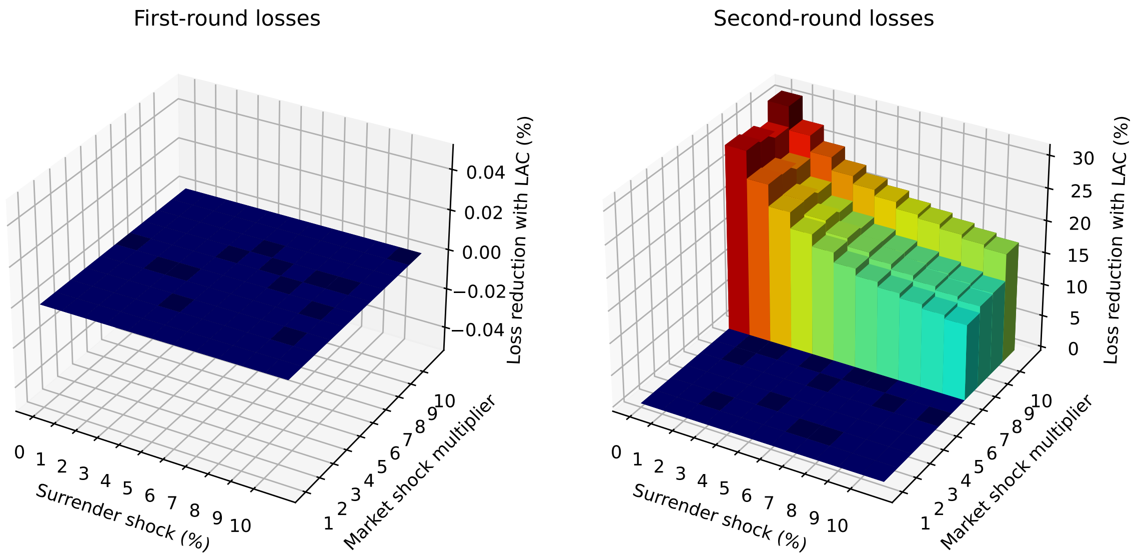

Figure 16: Reduction in market losses for funds due to LAC.
Source: Authors' calculations.