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RISKS

The impact of extreme cyber events on capital markets and insurers' asset portfolios

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Lance Levy, **Capco CEO**

THE IMPACT OF EXTREME CYBER EVENTS ON CAPITAL MARKETS AND INSURERS' ASSET PORTFOLIOS

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ABSTRACT

We study the extent to which extreme cyber-risk events affect capital markets and propose a concrete model framework that might be implemented in internal risk models of insurance companies. The literature on disaster risks looks at extreme scenarios in an area of 15% or larger decline in GDP (world wars, financial crises), while the cyber scenarios discussed in the literature are typically of smaller magnitude, i.e., up to 2% of GDP; only some very extreme cyber scenarios go up to 10% of GDP. To empirically analyze the relationship between extreme cyber risk events and capital markets, we implemented two models: a simple model based on historical data showing an impact of up to -4.26% on an insurer's assets for a stylized asset portfolio in two predefined cyber scenarios and an extended model in which we additionally implement the response of monetary policy and a consumption-based stock market response function. The latter model provides economically more sound estimators for the central parameters of interest (risk-free interest rate, credit spreads, stock returns, etc.) and shows an impact of up to -1.99% for the stylized insurer's asset portfolio. We conclude that the impact of extreme cyber risk events on capital markets exists so long as the asset side of insurance companies remains limited, which is mainly due to the hedging properties of different asset classes.

1. RESEARCH QUESTION

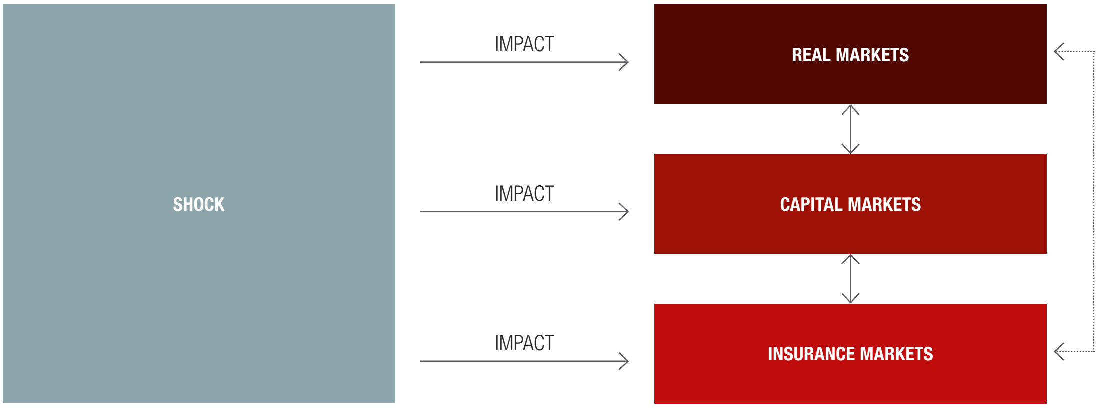
We study the impact of extreme (cyber) scenarios on the asset side of an insurer's balance sheet. While the effects of extreme scenarios on liabilities are relatively well understood and are a core feature of an insurer's risk modeling, relatively little is known about their potential implications on an insurer's assets.[2] For the purpose of this paper, we consider a representative, hypothetical insurer that holds a globally diversified portfolio with different asset classes, among which are stocks (equity), government bonds, and corporate bonds.

We consider the asset side of the insurer's balance sheet in isolation, while recognizing that interactions with the liabilities side is also important for interpretation of the results. We develop a general model to analyze the impact of extreme scenarios that we calibrate with information on extreme cyber scenarios. However, the model is formulated in such a way that it can be applied to different extreme events.

In Figure 1, we consider different types of shocks and their effect on the real economy, capital markets, and insurance markets. A shock can in principle be any extreme event, such as natural or man-made catastrophes, pandemics, extreme

[1] We acknowledge the support of Marcel Freyschmidt, Patricia Lehmann, and Dingchen Ning (University of St. Gallen), as well as comments and support from Eric Durand, Peter Middelkamp, Stephan Schreckenberg, and Jolanta Tubis (Swiss Re). An extended version of the article that contains all data, a complete formal description of the models, and more robustness tests is available from the authors upon request.
[2] In most internal risk models, the link is either neglected or modeled in a simplistic way, based on expert judgment.

Figure 1: Impact of a shock on real markets, capital markets, and insurance markets



cyber events, and wars. While our focus in this article is on cyber risk, other shocks have similar economic transmission mechanisms, hence we can also use historical observations from these other events to better understand the potential implications of an extreme cyber incident. Our motivation for doing this is that extreme cyber risks have not yet been observed historically, meaning that a direct empirical analysis is not possible.

A shock might have a direct impact on real markets. On one hand, it can result in reduced economic activity by hindering production (typically damaging the capital stock) and reducing consumer spending, while on the other hand, a shock might also increase economic activity due to the need for rebuilding the damaged capital stock (i.e., reconstruction after a catastrophic event). Because of these different effects, the impact on sectors might differ as well. Some studies have found that while cyber events cause a fall in the market value of the affected companies, they also helped certain IT security providers gain in market value.[3] We also saw how some biotech firms benefited from the COVID-19 pandemic.

A shock can also directly affect capital markets. The uncertainty created by an extreme event changes investor confidence and expectations, for example, about monetary and political interventions. Different types of events (e.g., natural versus man-made) might induce different changes in expectations, especially when diversification potential is considered. For example, regionally limited natural catastrophes can be diversified in a global portfolio, so long as they do not hit a critical economic center such as San Francisco or Tokyo and that the effect does not ripple through major supply chains.[4] Global events like the current pandemic, in contrast, are undiversifiable.

Through underwriting, a shock also has a direct effect on an insurer's liabilities. The direct loss (property loss and lives lost) is relevant for both the life and non-life insurance companies. There could also be various indirect links that need to be considered. For example, a decline in economic activity in real markets might impact expectations in the capital markets and reduce insurance demand. Conversely, an adverse development in the capital markets might negatively impact the supply of capital to the real economy and reduce the investment returns of insurance companies' portfolios. A difficult underwriting event might force insurers to liquidate some assets, putting pressure on the capital markets and potentially increasing insurance prices for the real economy.

[3] Cavusoglu et al. (2004) find that stock prices of information security providers increase on average by 1.36% after the announcement of another company's security breach.

[4] According to a study by Risk Management Solutions (1995) cited in Cummins (2006), a severe earthquake in Tokyo could cause losses in the range of U.S.$2.1 to U.S.$3.3 trillion, representing between 44% and 70% of the GDP of Japan.

2. LITERATURE REVIEW

Existing cyber-risk research uses the event study methodology to investigate the impact of data breaches or other cyber-risk events on the market value of firms. For example, Cavusoglu et al. (2004) show in an event study that a security breach negatively affects a company's stock price. They estimate the loss to be 2.1 percent of the market value, or U.S.$1.65 billion, per security breach. Campbell et al. (2003) and Hovav & D'Arcy (2003), on the other hand, find only limited evidence that data breaches or denial of service (DoS) attacks negatively impact the company's stock price. However, Campbell et al. (2003) provide evidence that a breach of confidential data has a larger negative effect on the stock price than a breach of non-classified information; Hovav & D'Arcy (2003) show a negative price effect for companies with a business model that is heavily based on the internet. Thus, the markets seem to behave rationally, as the discount is proportional to the expected loss associated with different data.

To overcome data limitation and to raise attention for the potential relevance of cyber risks among policymakers, media, the public, and executives, a variety of scenarios have been proposed in the applied business literature and in industry studies. These worst-case scenarios include various incidents that lead to a disruption of critical infrastructure and, thus, to more extreme economic losses. The economic effects of the scenarios show some extreme variations, ranging from 0.2% to 2% of the GDP in the year of the event with a few extreme scenarios going as far as 10% of world GDP [Eling et al. (2020), Ruffle et al. (2014)].

Overall, since there have been no extreme cyber events so far, the literature that investigates the effect of cyber risk on the economy and financial markets remains relatively limited. The largest cyber loss has been Wannacry with U.S.$8 billion economic loss [Gallin (2017)]. Based on the results presented by Mahalingam et al. (2018), one might argue that for an event to be so extreme to create an impact on the capital markets, an economic loss of at least U.S.$1 trillion (or 1-2% of world GDP) is necessary. The extreme magnitude needed is quite likely the reason why event studies for other catastrophic events arrive at mixed and inconclusive results [Wang and Kutan (2013)].

The fact that there has been no systematic impact of cyber-risk shock events, or other types of risks for that matter, does not, however, necessarily mean that such an impact does not exist. It might well be that investors in capital markets anticipate that large extreme events might happen and thus require a disaster risk premium, especially for companies that are more exposed to selected aspects of disaster risk. This idea has been included in recent asset pricing models, which show that rare disasters influence financial markets and are relevant for pricing. Barro (2006) uses rare disasters, those leading to a GDP loss of more than 15% (such as world wars, severe depressions, oil price shocks), over a 100-year period to explain the risk premia observed in the financial markets. He shows that investors do indeed demand a disaster risk premium, in the sense that higher-risk premiums are required to compensate investors for bearing the risks of extreme events. Since data on real disasters are scarce, Berkman et al. (2011) propose a crisis index that reflects expectations about potential disasters (disaster risk), instead of actual observations. They show that their disaster index has a large impact on the mean and volatility of stock markets and that industries with higher exposure to disasters yield higher returns.

In conclusion, several papers address the potential of rare disasters to explain the aggregate stock market development, such as mean returns and their variances, and find that disaster risk is relevant for asset pricing and could help explain certain aspects of a number of widely discussed asset pricing puzzles (such as the equity premium puzzle). It is also notable that the economic implications of extreme cyber scenarios do not currently seem large enough to expect a big impact from these events on the capital markets. The aforementioned studies usually consider shocks that result in a 15% fall in a country's GDP, our extreme cyber scenarios are typically around 2% of GDP. Event studies show that for a large diversified portfolio the impact of severe catastrophes on the capital markets should not be extreme. However, typically natural catastrophes are considered, which can be diversified globally, while that might not be the case with cyber risks. Furthermore, the results for man-made catastrophes, such as 9/11, show that there could be some impact on volatility and correlation, potentially due to the political reactions that investors anticipate.[5]

[5] Also for 9/11, most market indices recovered to pre-9/11 levels within a month [Mahalingam et al. (2018)]. More recently, the impact of other extreme non-diversifiable events, such as the risk of a pandemic, might be considered; the maximum drawdown for the MSCI World has been one-third (from 2400 on February 21st, 2020, to 1600 on March 23rd, 2020), but by the end of May it was already back to 2200. It is difficult to disentangle the effects of the crisis caused by the pandemic from certain response measures, such as the activities of central banks. For this reason, it is important to also model the response of the monetary authorities when analyzing extreme events.

We also note that while the aforementioned event studies of cyber risk predominantly focus on stock prices, we are also interested in the risk-free interest rates and credit spreads. The only paper we found that looks at the topic more holistically (not only stocks) is the working paper by Swanson (2019), which is based on a theoretical model and is not an empirical paper. We will implement some aspects of the model by Swanson (2019) to analyze the potential impact of extreme scenarios empirically.[6]

Table 1: Cyber scenarios

ELING ET AL. (2020)	RUFFLE ET AL. (2014)
Scenarios based on input-output model	Sybil logic bomb scenario analyzed using the Oxford Economics Model
Modeling of inoperability and recovery time across sectors, including spillover effects	Estimate the potential shock to the global GDP when a critical IT provider is compromised
0.64%-1.55% of GDP	4.7%-10.1% of world GDP

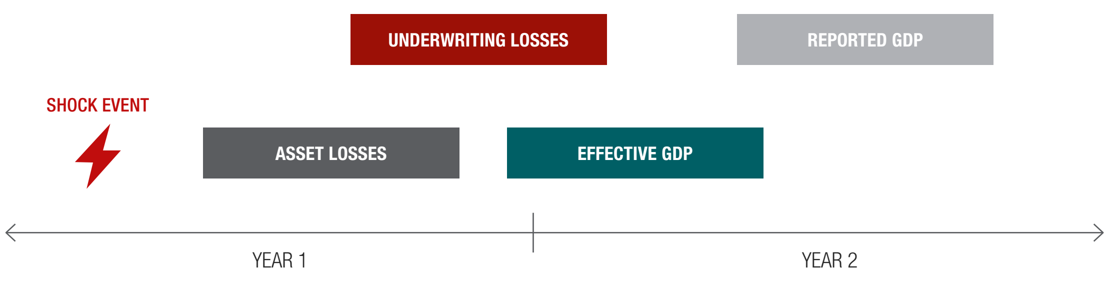
3. METHODOLOGY

We build on previous scenarios that model extreme cyber events and their impact on the economy. Most of these cyber scenarios do not estimate the effects on financial markets but provide an estimate for the potential losses to the economy. These numbers, and the applied methodologies, are very heterogeneous across different scenarios. Some estimate the loss for a certain sector or a certain region. The types of costs included in these estimates are also different. Some contain estimates for liabilities, some for the business interruption, and only a few estimate comprehensive aggregate economic losses. To derive the effects on the overall capital markets, we aggregate the losses at the country or at the global level, i.e., the country GDP or "world GDP" [as done in the input-output model by Eling et al., 2020], taking the geographical and sectoral dependencies into account. We use the two scenarios presented in Table 1 to illustrate our approach.

A model needs to consider shocks due to cyber-risk scenarios to both the underwriting and an insurer's assets. Thus, we need to model the connection between the estimated aggregated losses and the financial markets. However, it is difficult to identify an empirical relationship between the real economy and the stock market. The reason is that the forward-looking characteristics of the stock market and mitigations by monetary policy blunt the empirical relationship. For a stylized two period model (that is, a short-term shock) the situation could be described as shown in Figure 2.[7]

The assets would react quickly to the shock, long before the real economy (especially the delayed economic indicators) is reflecting the new situation. If we assume that financial markets do not make systematic errors in the relevant estimations, we can empirically estimate the relationship between the asset market price and the realized GDP. In the following section, we evaluate an empirical model where the severity of a cyber scenario, measured by a shock in GDP, is mapped on the severity of previous crisis events. The financial market reaction of these previous mapped events is then used as an estimate for the effects of a cyber scenario on financial markets. With this – as for any other statistical interference – we assume that a cyber scenario's effect on the asset market is comparable to other extreme events observed in the past.

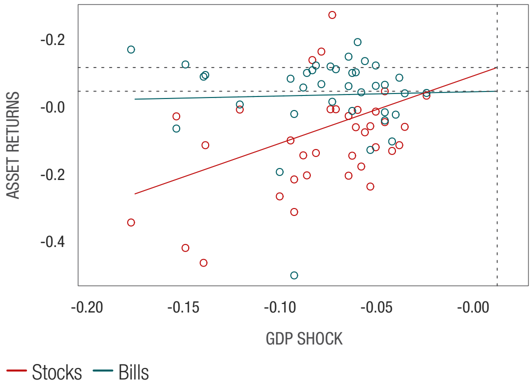
Figure 2: Stock timeline



[6] Swanson (2019) also notes that traditional macroeconomic models typically ignore asset prices and risk premia, while at the same time, traditional finance models typically ignore the real economy, emphasizing the lack of holistic research.

[7] To understand the empirical relationship between GDP and stock markets, we also consider the empirical correlation between GDP and stock markets (e.g., world GDP against MSCI World). Our results confirm what is known from Ritter (2005), i.e., the correlation is negative; with a lag of one year, the correlation is positive (0.27 for the world GDP against MSCI World).

Figure 3: Asset prices (y-axis) versus GDP shock (x-axis)



Note: The data contains a selection of asset returns and GDP shocks for the period between 1900-2016 for different countries. Both asset returns and GDP are annualized.

4. EMPIRICAL ANALYSIS

4.1 Simple model

One advantage of the following simple approach, which purely looks at the empirical relationship between realized GDP losses and asset prices, is that it not only incorporates the shock on asset returns due to a change in fundamentals, but it implicitly also takes into account changes in other pricing relevant parameters as well (such as changes in risk premium, risk aversion, sentiment, and monetary policy). We estimate the linear model $r = \beta_0 + \beta_r(\Delta y)$, where r stands for the asset returns (either stocks or bonds), Y for the GDP, y for logarithm of Y, and Δy for the percentage changes in the GDP. Using an extended version of the data from Barro (2006) for 53 global events between 1900 and 2016, we derive the relationship between GDP shocks (x-axis) and the reaction in the stock and bond markets (y-axis; see Figure 3). The data is available from the authors upon request.

As expected, the extreme events lead to a negative return on the stock market. Moreover, the treasury interest rates decrease with the shock size. This can be explained by flight-to-security and monetary interventions in times of crises. Lower short-term interest rates would mean an increase in risk-free bond prices with short-term maturity. Thus, the allocation to government bonds serves as a hedge against the shock to the other assets and liabilities.

We approximate the shocks to the value of government bonds Δgb as the shock to the risk-free interest rate Δi_{rf} (treasury bill) times the interest rate sensitivity D [modified duration; Ruffle et al. (2014)], i.e., $\Delta gb \approx -D(\Delta i_{rf})$. For corporate bonds, we use a similar approach. However, we need to additionally account for the change in credit spreads ψ_c. The credit spread is the difference in the yields on corporate and government bonds. Thus, the corporate bonds yield is defined as $i_{cb} = i_{rf} + \psi_{cb}$. In times of crisis, it is likely that the default probability of companies increases and so does the credit spread. Thus, we have $\Delta = \hat{\psi}_{cb} + \hat{\beta}_{\psi_{cb}} \Delta y$. We assume that the credit spread ψ_{cb} increases linearly with negative GDP shocks [Gilchrist and Zakrajšek (2012), Swanson (2019)].[8] The change in value of corporate bonds would then be proportional to the change in risk free interest rate plus the change in credit spreads, i.e., $\Delta cb \approx -D(\Delta i_{rf} + \Delta \psi_{cb})$. The duration is again set as for government bonds. The change in stock prices is modeled according to the regression underlying Figure 4 (i.e., the sensitivity to GDP changes is 2.0073).

Table 2: Parameter choices for simple model

PARAMETER		VALUE	SOURCES
GDP growth	$(\Delta\bar{y})$	2.2%	Historical average global yearly GDP growth [Barro (2006)]
Risk-free interest rate	$\hat{i}_{rf}$	1.7%	Historical average risk free (treasury bill) interest rate [Barro (2006)]
Duration	D	5.7	Average duration of non-life insurers' assets in 2019 [EIOPA (2019)]
Credit spread	$\hat{\psi}_{cb}$	2.0%	Difference between investment grade corporate bonds and government bonds, historical average (1973-2010) for U.S. corporate bonds (excl. financials) [Gilchrist and Zakrajšek (2012)]
Credit spread cyclicality	$\hat{\beta}_{\psi_{cb}}$	-0.34	Difference between investment grade corporate bonds and government bonds, historical average (1973-2010) for U.S. corporate bonds (excl. financials) [Gilchrist and Zakrajšek (2012)]

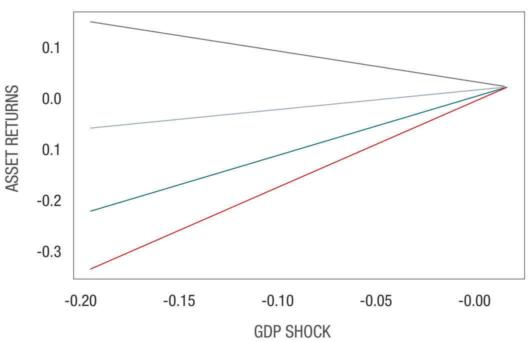
[8] Gilchrist & Zakrajšek (2012) measure the difference between investment grade corporate bonds and government bonds as historical average from 1973 to 2010 for U.S. corporate bonds (excluding financials). It would be intriguing to add credit spreads to Figure 3, but due to data limitations this is only possible for some of the points plotted in Figure 3 (historical credit spreads are only available for the U.S., but not for many of the markets included in Figure 3).

Table 3: Input parameters and results for the simple model

VARIABLE		BASIS SCENARIO	ELING ET AL. (2020) SCENARIOS		RUFFLE ET AL. (2014) SYBIL LOGIC BOMB		ASSET WEIGHT
Absolute GDP growth	Δy	2.20%	1.56%	0.65%	-2.50%	-7.90%	
Relative shock GDP	$(\Delta \tilde{y})$	0.00%	-0.64%	-1.55%	-4.70%	-10.10%	
Risk-free interest rate	i_{rf}	1.70%	1.63%	1.52%	1.15%	0.52%	
Government bonds return	Δgb	0.00%	0.43%	1.03%	3.13%	6.72%	50.00%
Corporate bond yield	i_{cb}	3.70%	3.84%	4.05%	4.75%	5.95%	
Corporate bonds return	Δcb	0.00%	-0.81%	-1.97%	-5.98%	-12.85%	30.00%
Stock market return	i_e	8.70%	7.51%	5.81%	-0.06%	-10.13%	
Equity return	Δe	0.00%	-1.19%	-2.89%	-8.76%	-18.83%	20.00%
Insurer's portfolio return	Δp	0.00%	-0.27%	-0.65%	-1.98%	-4.26%	

For the two cyber scenarios introduced above, we calculate the change in the value of a typical insurance investment portfolio and assume a 50% allocation to risk-free investments (government bonds, other relatively risk-free investments), 20% to stocks (equity), and 30% to corporate bonds (or other investments with a credit spread) [Gal et al. (2016)]. For simplification, we do not model other investment classes, such as real estate or alternative investments. The chosen parameters and results are presented in Tables 2 and 3. With this, we build a prototypical portfolio for an insurer's assets composed of government bonds, corporate bonds, and stocks and calculate the change in the portfolio as $\Delta p = \Delta \cdot w$, where the vector of returns on different assets is $\Delta = (\Delta gb, \Delta cb, \Delta e)$ and w is the portfolio weights.

Figure 4: Asset returns for different GDP shocks



The analysis shows that government bonds generally perform well and increase in value in cyber scenarios. We also see that the shock to corporate bonds is composed of two elements: first, the reduction in interest rate increases bond values and second, the increase in credit spreads decreases the bond value. In our case, the second effect dominates the first one. Still, the hedging property of government bonds would compensate most of the losses on the other positions so that even for the most extreme scenario (-10.1% GDP) the value of the insurer's assets would only decrease by -4.26%. The magnitude of this decline seems plausible in light of the aforementioned results of the literature review. We also present the results for a continuum of shock sizes in Figure 4.

While this first empirical analysis is useful in terms of getting an overview of the possible direction and economic magnitude, there are numerous limitations we need to address in order to arrive at an economically more profound analysis. Firstly, it must be recognized that modified duration only applies to incremental changes, not to 10% changes. Secondly, we need to take the interactions with the liability side into account (the modified duration used here only applies to the asset side, but to understand the economic impact of an interest rate change, we need to look at both sides of the balance sheet). Finally, we need to be cognizant of the fact that the results presented here are sensitive to outliers in the data and to changes in the input parameters (e.g., modified duration, asset weights). We need more detailed specifications in order to model the assets of a specific insurer adequately. To start with, the weights for the different asset classes need to be adapted. Second, differentiation between bonds with different rating (i.e., AAA, BBB, non-investment grade) would yield more realistic results. And last, the geographical asset allocation needs to be taken into account. The data used in Barro (2006) makes projections for individual economies, but not for the world GDP. For a worldwide diversified portfolio, we might thus expect fewer extreme effects.[9] However, it is also not completely clear how far extreme cyber scenarios can be diversified globally. One disadvantage of our empirical approach is that we assume that a cyber event would affect the economy and financial markets in a similar way as previous events. For example, the financial crisis of 2008 had a large impact on the financial markets but a relatively small impact on the real economy and thus might not be representative of a cyber event that affects the real economy (i.e., reduction in production efficiency). For this reason, we recommend digging deeper on the modeling side (see the extended model).

4.2 Extended model

The extended model relies on the macroeconomic model presented by Swanson (2019). We assume that a cyber event reduces the efficiency of production via a technological factor. We consider a classical (Cobb-Douglas) production function, where the production (Y) is a function of labor (l), capital (k), and the employed technology (A), i.e., $Y = A \cdot k^{1-\theta} \cdot l^{\theta}$. We assume that the labor and capital supply is exogenous and does not, therefore, change due to the shock. The shock to the technology factor translates one-to-one to a shock in the production; we assume that, in equilibrium, production equals consumption. With respect to the GDP dynamics over time, we assume that after the initial shock, $\Delta\widetilde{y}$, in the first period, the output returns to the long-term growth path. This would mean that the growth rate in period 2 is bigger than the long-term growth rate in order to compensate for the output lost. In robustness tests (available upon request) we consider alternative scenarios where the GDP deviates from the long-term growth path by more than one period.

We model the behavior of the monetary authority by using the so-called Taylor rule [Swanson (2019)]. The Taylor rule describes how the short-term interest rates (target rate, such as the three-month Libor) are changed in response to a shock to the GDP. It has been shown that nonlinear versions of the Taylor rule fit the behavior of monetary authority best [Nitschka and Markov (2016)]. The most frequently used nonlinear model is the logistic function [Gerlach and Lewis (2014)] $\Delta i_{rf} = \frac{i_{max}}{1+e^{-\beta_M \cdot \Delta y}} - i_{min}$, where i_{max} and i_{min} are the upper and lower limits for the possible interest rates, β_M is the slope of the response function, and $\Delta y = \Delta ln(Y)$ is the output gap (in %).[10] Thus, a negative output gap $\Delta y < 0$ would cause central banks to lower interest rates. However, compared to a simple linear Taylor rule, this function describes a s-shaped reaction, meaning central banks are reluctant to lower already low interest rates further or even push them into negative territory. The reason is that while there is little evidence that lowering interest rates below zero would further stimulate the economy [see liquidity trap; Krugman et al. (1998)], negative interest rates harm society by reducing pensions and savings.[11]

To complete the modeling of the interest rates, we need to analyze the effect of the short-term interest rates on the longer end of the yield curve. Thus, we use the monetary reaction function as an input to model yield curves for government bills (risk free), corporate bonds, and stocks. We refer to an extended version of the paper available upon request for more details about modeling yield curves. Combined with the interest rate sensitivity, we also calculate the shock to government bonds. For corporate bonds, we again consider countercyclical credit spreads and define them as in the simple model above. For stocks, we use the classical Gordon growth model and discount the companies' future cash flows to attain the present value with a shock $(\widetilde{S})$ and without a shock (S). Again, we refer to the extended version of the paper (available upon request) for all modeling details. We consider stocks as a leveraged claim on the overall consumption C^{λ}, where λ is the leverage [Abel (1999), Bansal and Yaron (2004), Gourio (2012), Swanson (2019)].[12] The expected return for stocks is composed of the risk-free interest rate and the equity risk premium, $i_e = i_{rf} + \psi_e$. Like the credit spread above, we assume that the equity risk premium increases in times of

[9] We note, however, that the U.S. accounts for approximately 50% of the MSCI World and 25% of global GDP. In this respect, there are also strict limits to diversification for the global market portfolio.

[10] To calibrate the logistic function, we use long-term average maximum (i_{max} = 6%) and minimum (i_{min} = 0.5%) for the interest rate. Swanson (2019) explicitly models the monetary response as a function of the output gap (i.e., in our context the GDP reduction) and inflation. We do not explicitly model inflation and focus instead on the effect of the GDP reduction only.

[11] Note that the Taylor rule describes short-term interest rates only; it would be possible to also include monetary interventions at the longer end of the yield curve (so called quantitative easing, yield curve control), which might reduce long-term interest rates and credit spreads. A more aggressive monetary intervention would thus generally support asset prices and further dampen the shock to the insurer's portfolio.

[12] The leverage parameter describes the leveraged claim on a company's future cash flows. This is due to fixed costs (operation leverage) and fixed amount of debt (financial leverage) [Gourio (2012)].

Table 4: Parameter choice for extended model

PARAMETER		VALUE	SOURCES
Monetary policy response	$\hat{\beta}_M$	0.70	Carvalho et al. (2018, table 1a) for U.S.; other sources: 0.75 [Swanson (2019, p.13)], 0.5-1 [Taylor (1993, 1999)]; empirical for Switzerland (2000-2012) 0.58-0.63 [Nitschka and Markov (2016, table A.3)]
Min. interest rates	i_{min}	0.5%	Nominal short term interest rates observed for the U.S.
Duration	D	5.7	Average duration of non-life insurers' assets in 2019 [EIOPA (2019, p. 71)]
Risk premium cyclicality	$\hat{\beta}_{\psi_e}$	0.97	Empirical sensitivity of the equity risk premium to shocks in GDP for U.S. equity (1948-2005) [Cooper and Priestley (2009, p. 2808)]
Leverage	$\hat{\lambda}$	3.0	Assumption by Swanson (2019, p. 18) based on estimated/model derived values in Abel (1999)/Bansal and Yaron (2004)

Table 5: Input parameters and results for the extended model

VARIABLE		BASIS SCENARIO	ELING ET AL. (2020) SCENARIOS		RUFFLE ET AL. (2014) SYBIL LOGIC BOMB		ASSET WEIGHT
Absolute GDP growth	Δy	2.20%	1.57%	0.65%	-2.50%	-7.90%	
Relative shock GDP	$(\Delta\tilde{y})$	0.00%	-0.63%	-1.55%	-4.70%	-10.10%	
Risk-free interest rate	i_{rf}	1.70%	1.32%	0.96%	0.55%	0.50%	
Government bonds return	Δgb	0.00%	0.36%	0.70%	1.09%	1.14%	50.00%
Corporate bonds yield	i_{cb}	3.70%	3.54%	3.48%	4.15%	5.94%	
Corporate bonds return	Δcb	0.00%	0.15%	0.20%	-0.43%	-2.09%	30.00%
Equity premium	ψ_e	8.70%	8.93%	9.46%	12.11%	17.30%	
Equity return	Δe	-0.00%	-0.48%	-1.14%	-4.13%	-9.68%	20.00%
Insurer's portfolio return	Δp	-0.00%	0.13%	0.18%	-0.41%	-1.99%	

crisis, thus $\psi_e = \hat{\psi}_e + \hat{\beta}_{\psi_e}\Delta y$. Such a countercyclical equity risk premium is well documented in the literature [Campbell and Cochrane (1999), Swanson (2019)]. Table 5 reports the changes in the value of an insurer's portfolio for different scenarios (the parameters are chosen as in Tables 3 and 4).

While the sensitivity of the insurer's portfolio to shocks is slightly lower here than in the empirical model above, the results are quite similar. For the most extreme GDP shock (-10.1%), the portfolio return would be -1.99% (compared to -4.26% above). The difference between the simple and expanded models is mainly driven by the different interest rates used to calculate the assets sensitivity. Here, we calculate the assets' sensitivities to the longer end of the interest rate curve, which is less sensitive to the shock than the short-term interest rates used above.

Figure 5 shows the return on the insurer's portfolio for the whole space of different shocks. Compared to the results above, the curves are now concave and not linear anymore. The reason for that is that here we assume that the monetary authority reaction is limited. For corporate bonds and the whole insurance portfolio, the curves are first increasing and then decreasing for larger shocks. The reason is that for small shocks the monetary authority dominates (risk-free rates) but for larger shocks, the credit spreads and equity risk premia start to bend the curves downwards.

4.3 Robustness checks

To judge the reliability of our results, we let all estimated parameters vary over a meaningful range of values. One important parameter is how the monetary authority reacts with

Figure 5: Asset returns for different GDP shocks (extended model)

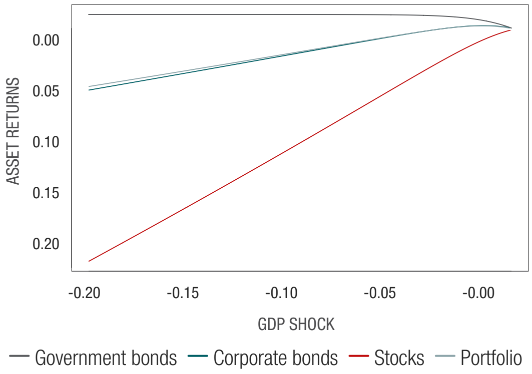


Figure 6: Portfolio returns for different monetary policies (β_M)

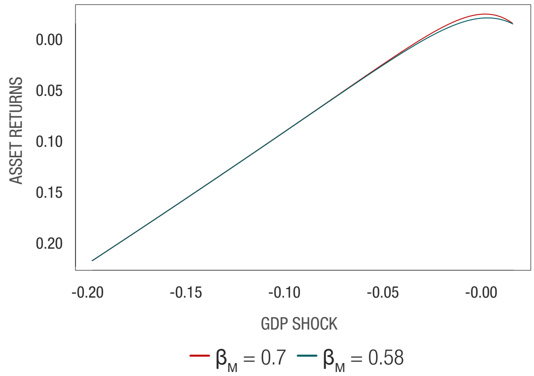


Figure 7: Portfolio returns for different monetary policies (extended model; i_{min})

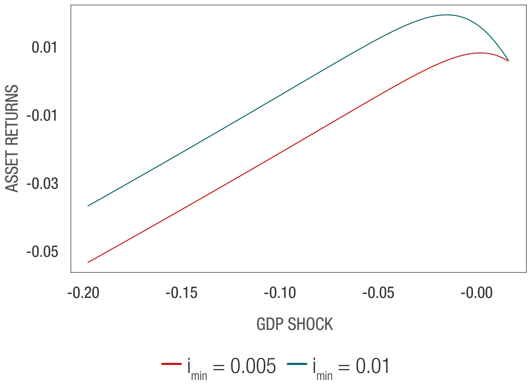
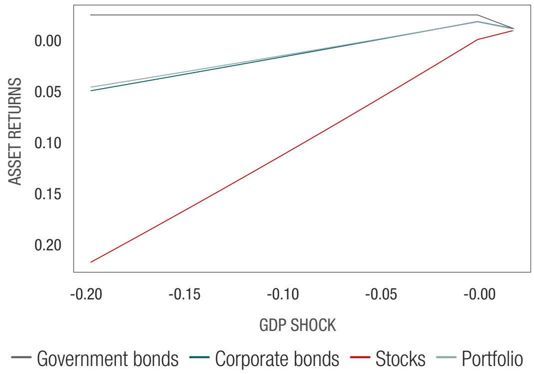


Figure 8: Portfolio returns for linear Taylor rule



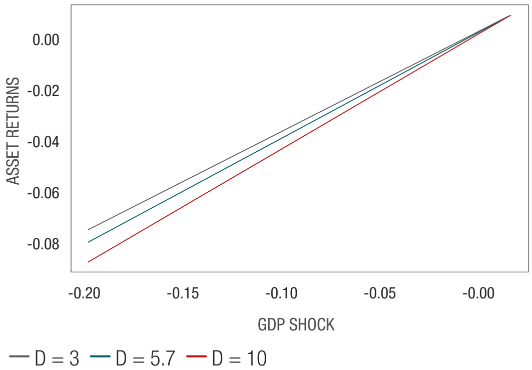
interest rate cuts to the shock, $\hat{\beta}_M$. Figure 6 shows the return on the insurer's assets for different $\hat{\beta}_M$. A less aggressive lowering of interest rates as a reaction to a shock ($\hat{\beta}_M = 0.58$) would decrease, ceteris paribus, the present value of all assets and the negative shock to the insurer's aggregated assets would be larger. The government bonds would especially benefit from lowering interest rates. Hence, essentially if we believe that central banks will react to the shock, there will be no negative impact on asset returns. It would be possible to also include monetary interventions at the longer end of the yield curve (so-called quantitative easing), which might reduce long-term interest rates and credit spreads. A more aggressive monetary intervention would support asset prices and further dampen the shock to the insurer's portfolio.

Another important parameter is how the monetary authority reacts with interest rates cuts to the shock, i_{min}. Figure 7, shows the return on the insurer's assets for different i_{min}. A more aggressive lowering of interest rates as a reaction to a shock (i.e., i_{min} = -1%) would increase, ceteris paribus, the present value of all assets and the negative shock to the insurer's aggregated assets would be smaller. Hence, essentially if we believe that the central banks will react more strongly to the shock, there will be less negative impact on asset returns.

We not only let the parameter values vary to analyze parameter risk, but we also vary the modeling itself to get a better understanding of the potential model risk. An alternative to the logistic model for the monetary response is to use a simple linear function, which is cut off at the minimum and maximum interest rates, again showing robust results (see Figure 8).

We also analyze the sensitivity of our results to the duration (focusing on the effects on the assets only; for the influence of the interest rate change on the entire risk capital of an insurer, the liabilities are relevant as well). Figure 9 presents the return on the insurer's asset portfolio for different duration levels based on the simple model. A portfolio with higher duration would perform relatively worse.

Figure 9: Portfolio returns for different durations (simple model)



5. CONCLUSIONS, LIMITATIONS, AND FUTURE RESEARCH

We propose a general framework to model the effects of extreme risks on an insurer's assets and apply it in the context of extreme cyber risk events. We reviewed a wide range of literature, mainly for non-cyber disasters and show how we can apply the respective insights to future extreme cyber disasters and their impacts on the financial markets. Extreme cyber scenarios might have a profound effect on an insurer's assets, but the overall effect remains, to some extent, limited mainly due to hedging properties of different asset classes. First, such an event would lower current and expected interest rates and thus increase the value of (risk-free) government bonds. Due to this property, government bonds have frequently served as a safe haven in times of crisis. Second, the effect on corporate bonds is ambiguous, since in times of crisis we frequently observe spikes in credit spreads. Third, stocks would suffer major losses. The reason is that a cyber disaster would reduce the economy's productivity and capital stock. After the initial hit to the production, the economic multiplier would cause demand and production to plunge further. All this hurts companies' earnings and increases in the risk premium would further reduce the value of future cash flows. Overall, the value of stocks declines and credit risk goes up, but the risk-free interest rate decreases, which in turn increases the value of government bonds and other relatively risk-free investments. This important hedging property may exist when we only look at the asset side of the balance sheet of a (re-) insurer, but lower interest rates, particularly, may lead to a large increase in the market values of liabilities and materially impact solvency (via discounting used for market value margin/risk margin calculation).

There are a number of limitations to our analyses that might serve as motivation for future research. First, since we have never observed a catastrophic cyber event, we do not exactly know whether previous disasters are representative and whether different types of cyber events will have different effects on assets.[13] Second, for a real-life implementation, insurers need to adapt our model to reflect their concrete asset portfolio with respect to the geographic, asset class, strategic, and duration allocations. As mentioned above, there might be sectors that could even benefit from a cyber event (e.g., cyber security providers). From an empirical perspective, we illustrated that the main challenge is to identify the time dimension of the connections between an event and the reaction of the financial markets. Since financial markets are forward-looking, their reactions run in front of other relevant economic measures. By looking at several periods and using unexpected shocks, we could mitigate this problem to some extent. It also means that insurers should be aware that asset shocks might precede underwriting losses for cyber risks. The timing of the losses is thus different, which again might cause some diversification potential. However, insurers will need to put provisions on the balance sheet as soon as the cyber event occurs.

Future research could aim to provide better estimates for the potential economic damage a cyber disaster could cause. We addressed the uncertainty so far by providing results for a whole range of shock severities, as measured by the GDP decline. Clearly, for risk management purposes, we should have a more sophisticated understanding of the size of the shock, the time it takes for the crisis to resolve, and the likelihood of such an event. Moreover, to apply our model to the concrete exposure of an insurer, we would need to be more precise about the sectoral and geographical regions that are affected. An input-output model as presented in Eling et al. (2020) could be informative on such questions. Furthermore, this analysis is limited to studying the implications of such shocks to the asset side of the balance sheet of an insurance company. To understand the full impact on the balance sheet of an insurance company, the liability side also needs to be incorporated in the analysis, which is not the focus of this analysis. In addition to the impact of an extreme scenario on the insured losses, the interest rate effects also need to be considered. Furthermore, the increase in credit spreads might also have an impact on the underwriting side.

[13] For example, we look at scenarios where stock prices go down, but what we have not considered is what happens if a cyberattack directly disrupts trading on the capital markets. For example, what happens if virulent malware stops the NYSE exchange for two weeks, or what happens if malware disconnects an insurance company from the capital market for two weeks?

Another promising avenue for future research might be to apply our model to other institutions in the financial services sector, especially to the banking industry. The findings in this paper indicate that the impact of extreme scenarios on the asset side of the insurer's balance sheet is relatively limited because of hedging effects, but it is not clear how the model would behave in the context of a banking balance sheet. The outcome of such an analysis might also provide some relevant policy implications on differences and commonalities in the business model of banks and insurance companies.

The results of the paper can be useful to improve internal capital models with respect to the link between extreme (cyber) events and the capital markets. The general results derived here are also relevant in light of the discussion around the development of solvency models that assume a linear correlation of 0.25 between the investment and underwriting.[14] Given the results we have seen so far, this seems too conservative. Moreover, the relationship should be modeled non-linearly, that is, in normal times the correlation is very likely lower and closer to 0, while in extreme scenarios we might expect to observe a link (e.g., 9/11), at least in the short- to medium-term. Given that the time horizon of solvency models is not short term (daily, weekly), but one year, the strengths of the actual correlation might again be questioned in light of the results presented here.

[14] A linear correlation of 0.25 is the assumption in many regulatory standard models, such as Solvency II in the European Union [Eling and Jung (2020)]. Insurance companies that work with internal models use our specific dependencies, including dependencies between investment and underwriting risks.

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