Macroeconomic and financial impacts of compounding pandemics and climate risk

Nepomuk Dunz[a,c], Andrea Mazzocchetti[b], Irene Monasterolo[c,d], Arthur Hrast Essenfelder[b,e], Marco Raberto[f]

[a] *The World Bank, USA*

[b] *Ca' Foscari University of Venice, Italy*

[c] *Vienna University of Economics and Business, Austria*

[d] *Boston University, USA*

[e] *Risk Assessment and Adaptation Strategies Division, Euro-Mediterranean Center on Climate Change, Italy*

[f] *University of Genoa, Italy*

Abstract

We develop a macrofinancial Stock-Flow Consistent model to assess the impacts of the COVID-19 crisis in Mexico. We analyse the interplay between banks' lending, government policy's effectiveness and the economic recovery. By embedding financial actors and the credit market connected to economic agents, and by endogenizing investors' expectations, the model allows us to assess the economy-finance feedback, providing a more accurate assessment of risks. Since COVID-19 did not occur in isolation but interacted with climate vulnerabilities, we develop a compound risk indicator to quantify the non-linearity of compounding COVID-19 and hurricanes on GDP through time. We find that credit market constraints can amplify the initial shock by limiting firms' recovery investments, thus mining the effectiveness of higher government spending. Moreover, when climate and COVID-19 risks compound, they give rise to non-linear dynamics that amplify losses, with implications on the economic recovery, banks' risk and public debt sustainability.

Keywords: COVID-19, government policies, banks' lending, climate change, compound risk, credit market constraints, Stock-Flow Consistent model.

E44, E40, E47, G21, Q01

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1. Introduction

The COVID-19 pandemic has generated a systemic economic shock that is unprecedented in scale. It affected several markets simultaneously and fast spread to public and private finance. According to the IMF´s latest World Economic Outlook (IMF, 2021), the COVID-19 recession is the deepest since the end of WWII - 7% output loss relative to the IMF´s 3.4% growth forecast of October 2019 – and its consequences will likely be long-lasting. Governments and central banks, both in high income and emerging markets, have reacted in an unprecedented manner to mitigate the socio-economic impacts of the epidemic, also in low-income countries (The World Bank, 2020a).

Recent research highlighted the implications of the COVID-19 crisis on public debt sustainability (Stiglitz & Rashid, 2020), on socio-economic inequality (Ahmed et al., 2020; Levy Yeyati & Filippini, 2021), and on financial stability (Andries et al., 2020; Adrian & Natalucci, 2020; Brunnermeier et al., 2020). On the banking side, Beck & Keil (2021) analysed the exposure of US banks to the COVID-19 crisis and their ability to support the economy with lending, finding that government support programs played an important role in increase in lending. Furthermore, a flourishing stream of research has focused on the design of government intervention during the COVID-19 epidemic and their the macroeconomic impacts (Boissay & Rungcharoenkitkul, 2020), finding that the effectiveness of government response measures depends on the conditions and targeting of those measures (Bayer et al., 2020; Guerrieri et al., 2020), and who is bearing their economic costs (Kaplan et al., 2020). Cox et al. (2020) highlighted that results about the effectiveness of government policy strongly depend on model assumptions and design. Eichenbaum et al. (2020) and Jones et al. (2020) incorporated a SIR (acronym for susceptible-infected- recovered or removed, developed by Kermack & McKendrick (1927)) feedback mechanism, to provide a dynamic interaction between economic activity and the epidemic spread.

However, three main research gaps remain to understand the macroeconomic and financial impact of the pandemic in the economy and finance. First, the macroeconomic analyses of the COVID-19 crisis have mostly focused on the direct impacts, neglecting the indirect impacts, and in particular their drivers and risk transmission channels, in the economy and credit market. Second, how revisions in banks' lending affect the implementation of government recovery policies and firms' investment decisions, and thus the timing and magnitude of the economic recovery, deserve attention. Third, current analyses neglected the fact that in several countries, COVID-19 did not happen in isolation but compounded with another source of stress, such as climate change (Phillips et al., 2020; Zscheischler et al., 2018), increasing the complexity of risk and of policy response (Battiston et al., 2020). For instance, by damaging the countries' productive capacity and socio-economic infrastructures, natural hazards provide a fertile ground for pandemics to spread (Mahul & Signer, 2020), delaying the economic recovery and exacerbating the long-run effects on financial stability. These impacts are characterized by complex macro-financial feedbacks, and their evolution can be largely influenced by policy introduction and by agents' expectations about their outcome (Battiston et al., 2021).

Addressing these three research gaps is crucial to inform the design of fiscal and financial policies aimed to build back better, strengthening economic and financial resilience to compounding risks.

It also introduces new challenges for macroeconomic analysis, as well as for fiscal and financial risk management, requiring adaptation of our analytical tools. The complexity and endogeneity of such risks require to smooth underlying assumptions of equilibrium, market-clearing prices and agents' perfect foresight. Moreover, it requires to embed financial actors and their risk assessment in macroeconomic modelling, in order to assess the feedback from financial agents' risk assessment to the economy and policy response (Monasterolo, 2020). Indeed, banks' sentiments (Dunz et al., 2021), i.e. their expectations about policy impacts, and internalization in their risk assessment, can lead them to revise lending conditions to firms, affecting their investment decisions. This, in turn, can influence the policy outcomes and the realization of the mitigation scenarios (Battiston et al., 2021).

In this paper, we introduce a theoretical development and application to quantitatively assess the impacts of the COVID-19 health crisis, either occurring as individual or compounding with climate physical risk, on the economy and credit market, considering the role of fiscal and monetary policies introduced in the COVID-19 crisis. Then, we analyse the sensitivity of government spending effectiveness to credit market constraints, and the implications for GDP recovery, banks and sovereign financial stability. We further develop the EIRIN macrofinancial model (Monasterolo & Raberto, 2018) and we calibrate it on Mexico, a country that is highly exposed to COVID-19 (in terms of number of contagion and deaths), is highly exposed to hurricanes, and deeply integrated in the global value chain, thus making it a potential channel of cascading risk (e.g. to the US).

EIRIN is a Stock-Flow Consistent model populated by heterogenous interacting agents of the economy and finance, endowed with adaptive expectations about the future of the economy. EIRIN is able to capture the richness of COVID-19 and climate direct and indirect risks transmission channels to agents and sectors of the economy and finance, considering how the nature of risk affects agents' heterogeneous beliefs, inter-temporal preferences, and the formation of expectations and decisions in response to shocks. Importantly, EIRIN includes a financial sector and market connected to economic agents, thereby enabling the analysis of financial feedbacks on endogenous investment and consumption decisions, and on policy effectiveness.

The remainder of our paper is organized as follows. Section 2 describes the theoretical methodology, focusing on the main characteristics of the EIRIN model. Section 3 presents the model initialization and calibration on Mexico data. Section 4 introduces the COVID-19 and compound risk scenarios while Section 5 discusses the simulation results. Section 6 concludes with policy recommendations to build back better.

2. Methodology

2.1. Overview

We extend the EIRIN macroeconomic model to analyze:

- To what extent and through which channels the COVID-19 crisis affects the banking sector's lending and financial stability;
- The procyclical feedback of revision of banks' lending on firms' investments and on the effectiveness of government fiscal policies in the economy recovery;
- The conditions for banks and economic loss amplification when COVID-19 shock compounds with climate physical risks (hurricanes).

The EIRIN model allows to consider the uncertainty and non-linearity that characterize COVID-19 and climate risks (Battiston et al., 2020), and their impact on investment and policy decisions. In addition, EIRIN considers the heuristics and behavioral patterns of agents and representative sectors that contribute to the generation of emerging phenomena and out-of-equilibrium states of the economy (Monasterolo & Raberto, 2018).

2.2. The EIRIN Model

With the EIRIN macrofinancial model (Monasterolo & Raberto, 2018, 2019) we analyze how compound COVID-19 and climate physical risks (e.g. hurricanes) affect the economy, the credit sector and public finance. EIRIN allows to consider the richness of compound risk transmission channels and impacts in the economy and finance; the role of agents' heterogeneous beliefs and expectations; the interplay between finance and public policy in the COVID-19 recovery.

EIRIN is a Stock-Flow Consistent (SFC) model of an open economy (Caverzasi & Godin, 2015; Dafermos et al., 2017; Dunz et al., 2021; Naqvi & Stockhammer, 2018; Ponta et al., 2018; Dafermos & Nikolaidi, 2021; Caiani et al., 2016) composed by agents and sectors, which are heterogeneous in terms of characteristics (e.g. income, wealth) and preferences, and are characterized by forward-looking expectations about the future of the economy and the transition. Agents and sectors include wage and capital-income earning households; an energy company and an utility company, which can produce electricity out of either fossil fuel or renewable energy; a capital good producer; a service sector, which includes tourism; an industry sector; a banking sector; a central government; a central bank; a foreign sector providing import and export of commodities and consumption goods. EIRIN's sectors are represented as a network of interconnected balance sheets items (Monasterolo & Raberto, 2018) calibrated on real data (when possible), making it possible to trace a direct correspondence between stocks and flows. The rigorous accounting framework allows to display the dynamic relations of agents and sectors' balance sheets and to analyze (i) the direct impact of the shock on individual agents and sectors of the economy (at the level of balance sheet entry), (ii) the indirect impact of the shock on macroeconomic variables (e.g. GDP, unemployment, interest rate) and financial risk variables (e.g. banks' Probability of Default, Non-Performing Loans), and (iii) the reinforcing feedbacks that generate in the financial sector and that could amplify the original shocks, leading to cascading economic losses. The finance - economy feedback is fundamental to assess the double materiality of climate risks (IIF 2021). In particular, it allows us to translate financial actors' expectations towards climate change and policy scenariosinto a revision of their risk assessment and thus of the cost of capital for firms, which in turn affects the feasibility of transition scenarios (Battiston et al., 2021).

This approach has several advantages for the assessment of risks of different nature, such as climate physical risks and pandemics, and to analyse them individually or compounding. First, we can quantitatively assess the richness of risk transmission channels and of impacts on heterogeneous agents and sectors of the economy and finance. Second, we can analyze the interplay between private finance, public policies, and economic growth, considering the sensitivity of public spending effectiveness to different levels of credit and labor market constraints, and identifying sensitive intervention points. Third, we can consider the deep uncertainty of climate-related risks and of pandemics (Battiston et al., 2020) that feeds into financial agents' risk assessment and reactions (e.g. banks' revision of lending policy).

Finally, EIRIN allows agents to depart from perfect foresight presence in scenarios of deep uncertainty about climate impacts. It also allows us to consider the presence of market imperfections (e.g. potential mispricing) and market power (e.g. in the energy sector).

We tailor the model to the characteristics of Mexico (Figure 2.2) by including:

- The tourism sector
- The service sector
- Migrants' remittances
- Import and export of commodities and consumption goods
- Government COVID-19 related spending (e.g. healthcare, unemployment measures).

Mexico is highly exposed to hurricanes and COVID-19 risk, and deeply integrated in the global value chain, thus making it a potential channel of cascading risk.

Figure 2.2 shows the framework of the EIRIN economy and its capital and current account flows among sectors.

The EIRIN economy is populated by heterogeneous sectors and agents. In particular, we can distinguish a working class sector (H_w), a capitalist household sector (H_k), a labor intensive consumption good producer (service sector), which also includes a touristic sector (Tu), (CGPl, abbrev. by C_l), a capital intensive consumption good producer (CGPk, abbrev. by C_k), a capital goods producer (K), an energy company (EN), a bank (BA), a central bank (CB), a government (G) and a foreign sector (ROW). For better readability we abstain from labeling variables within the same time period with a time index. Previous period's variables are labeled with the time index $t-1$.

For a more detailed description of all sectors, market interactions and behavioural equations, please refer to (Monasterolo & Raberto, 2018, 2019).

2.3. Markets

EIRIN's agents and sectors interact with each other and with the foreign sector through a set of markets:

- Consumption and capital goods markets
- Labour market
- Energy market
- Raw materials market
- Bonds market
- Credit market.

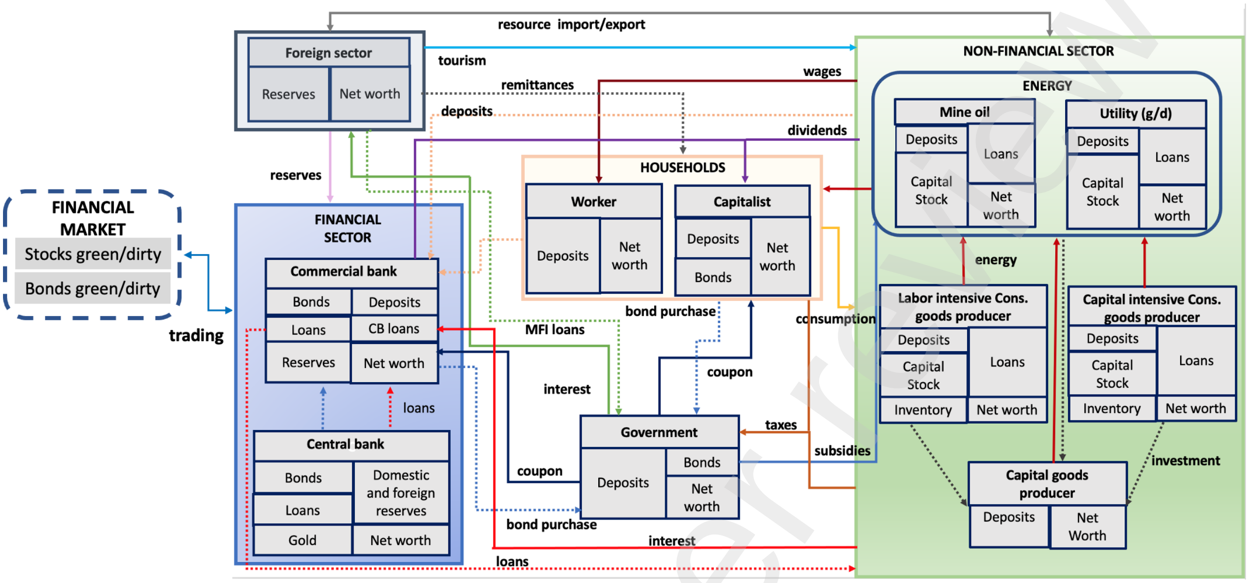


Figure 2.1: **The EIRIN model framework:** capital and current account flows of the EIRIN economy. For each sector and agent, a representation in terms of assets and liabilities is provided. The dotted lines represent the capital account flows, while the solid lines represent the current account flows. The model is composed of five sectors i.e. the non-financial sector, the financial sector, households, the government and the foreign sector. The non-financial sector is composed of (i) an energy firm that supplies energy to households and to firms as an input factor for production (red solid line); (ii) capital intensive (e.g. industry) and a labor intensive (e.g. service, tourism, agriculture) consumption good producers that provide households heterogeneous consumption goods (yellow solid line). The energy firm and the consumption good producers require capital as an input factor for production. To build-up their capital stock, they invest in capital goods (grey dotted line), which are produced by the capital good producer. To finance investment expenditures, firms can borrow from the commercial bank (red dotted line), which apply an interest rate to their loans (red solid line). Households, firms and the government have deposits in the commercial bank (pink dotted line). The commercial bank also holds reserves at the central bank (blue dotted line), that could provide refinancing lines (red dotted line). The government sector pays public employees. In case of the COVID-19 crisis and of climate shocks, the government provides emergency relief to households, purchases consumption goods and grants investment subsidies to firms (blue solid line). The government collects tax revenues from households and firms (brown solid line) and finances its current spending by issuing sovereign bonds (dark blue dotted line). Sovereign bonds are bought by capitalist households, by the commercial bank and by the central bank. Further, the government may receive loans from Monetary Financial Institutions (MFI, green dotted line). The government pays coupons (dark blue solid line) and interest (green solid line) respectively to the sovereign bonds and MFI loans (if applicable). Households are divided into workers and capitalists, based on their functional source of income. Worker households receive wage income (wine-coloured solid line). Capitalist households own domestic firms for which they receive dividend income (purple solid line) and coupon payments for their sovereign bond holdings (dark blue solid line). The foreign sector provides remittances (grey dotted line) and consumption goods to households (dark grey solid line), and resources to firms as inputs for the production factors (black solid line). The foreign sector also generates tourism flows and spending in the country (grey solid line), exports of service sector and industry goods (dark green solid line) and provides financial support to the government via MFI (green dotted line). Finally, it provides reserves to the domestic central bank (light purple solid line).

The formation of demand, supply and prices in each market (except for the credit market) are independent from each other at any given simulation step. In the credit market, demand depends on the demand for capital goods. The demand rationing affects the effective demand of capital goods by the CGPl and CGPk, and by the energy company. In each market, the prices are made by the supply side as a mark-up on unit costs. In addition, in the financial market, the sovereign bond price is determined based on the existing stock of public debt, and on the performance of the real economy.

2.4. Sequence of events

The sequence of events occurring in each simulation step is the following:

1. Policy makers take their policy decisions. The CB sets the policy rate according to a Taylor-like rule. The government adjusts the tax rates on labor and capital income, on corporate earnings, and on Value Added to meet its budget deficit target.
2. The credit market opens. The bank sets its maximum credit supply according to its equity base. If supply is lower than demand, proportional rationing is applied and prospective borrowers (i.e. the consumption goods producer F_K and F_L and the energy company EN) revise down their investment and production plans accordingly.
3. Real markets open in parallel. Prices of the exchanged goods or services are determined, then the nominal or real demand and supply are provided by the relevant agent in each market. Finally, transactions occur generally at disequilibrium, i.e. at the minimum between demand and supply.
4. The sovereign bond market opens. The capitalist household and the bank determine their desired portfolio allocation of financial wealth on sovereign bonds. The government offers newly issued bonds to finance a budget deficit, which includes the COVID-19 related expenditures. Then, new asset prices are determined.
5. All transactions and monetary flows are recorded, and the balance sheets of the agents and sectors of the EIRIN economy are updated accordingly (see Appendix A for the Balance Sheet matrix, the Cash flow matrix and the Net worth matrix of the EIRIN economy).

2.5. Agents and sectors' behavior

EIRIN's agents and sectors are characterized by the following properties:

Heterogeneous households (HH_w and HH_k). By building on Goodwin (1967) and the Lotka-Volterra's predator-prey model, households are divided into two classes, a working class (H_w) and a capitalist (H_k) income class, respectively. H_w lives on wages (Eq. 1), while H_k earns her income out of financial markets through government bonds' coupons and firms dividends (Eq. 2). Furthermore, both household classes receive remittance flows from abroad. Income class heterogeneity is functional to assess the distributive effects of the policies introduced for COVID-19 and/or disaster response, on the channels of inequality in developing countries. All households pay their energy bill and income tax. This leaves them with Y_m^{net} as net disposable income (Eq. 3), whereas remittances R_m sent from relatives across the world add to households' net disposable income. Households' consumption plans (Eq. 4) are based on the Buffer-Stock Theory of savings (Deaton, 1991; Carroll, 2001), which balances the *impatience* of households of consuming all their income and wealth right away with their *prudence* about the future preventing them to draw down their assets too far. This results in a quasi target wealth level that households pursue. Then, households split their consumption budget C_m between the two types of consumption goods, $\beta\, C_m$ to labor intensive and $(1-\beta)\, C_m$ capital intensive consumption goods.

$$\begin{aligned}
Y_{H_w} &= (N_{high} + N_{low})\ w && (1)\\
Y_{Hk} &= n_{bond}\ c_{bond} + \sum d_i && (2)\\
Y_m^{net} &= (1-\tau)\ Y_m - p_{EN}\ q_m^{EN} + R_m && (3)\\
C_m &= Y_m^{net} + \rho\left(M_m - \phi\ Y_m^{net}\right) && (4)\\
C_m^{F_L} &= \beta\ C_m && (5)\\
C_m^{F_K} &= (1-\beta)\ C_m && (6)
\end{aligned}$$

with $m = H_w, H_k$. $\sum d_i$ are the dividends received by the capitalist household H_k and R_m are the remittances received by the households.

We assume that skills are heterogeneous and uniformly distributed among workers, and that the capital intensive consumption good producer and capital good producer always employ workers with the highest skills, in exchange of higher salaries. Workers in the labor intensive consumption good sector require lower skills, thus receiving lower wages (Blanchard, 2017). Firms form adaptive expectations about future demand based on their sales in previous time periods. Those demand expectations then determine firms' production plan $\widehat{q_j^C}$. Labor demand N_j by both consumption good producers (with $j = F_L, F_K$) is determined by their production plan $\widehat{q_j^C}$, their capital endowment K_j and by the Leontief technology.

$$\widehat{N_j} = \min\left(\widehat{q_j^C}, \gamma_j^K K_j\right) / \gamma_j^N \tag{7}$$

where γ_j^K and γ_j^N are, respectively, the sector-dependent capital and labor productivity. This setup prevents the firm to hire more labor than necessary. The capital good producer only relies on labor as input factors, and hires workers based on its labor productivity to satisfy the firms investment demand for capital goods

$$\widehat{N_K} = \min\left(\sum_n \widehat{I_n}/\gamma_K^N,\ (1+\chi)\ N_{K,t-1}\right) \tag{8}$$

where $\widehat{I_{n,t}}$ represent firms' planned investment demand at time t, γ_K^N the labor productivity in the capital producer's sector and χ is an exogenous parameter which limits the maximum amount of workers that can be hired by the capital producer sector in one period. We assume labor supply to be fully elastic and employment is endogenously determined by labor demand. Wage setting for high and low-skilled workers is endogenous and set according to the average workers' skills in each sector (Eq. 10 and 9), following a Phillips curve-like rule (Keen, 2013). The average money wage growth (Eq. 11) depends on the employment level e (see Eq. 32), declining with rate $-\theta_1$ in case the labor force is entirely unemployed (i.e. $e = 0$) and growing with a maximum of $-\theta_1 + \theta_2$ (with $\theta_2 > \theta_1$ and $\theta_{1,2} > 0$) in case of full employment (i.e. $e = 1$). The steady state money wage, keeping the money wage constant, is is given by $e = \frac{\theta_1}{\theta_2}$. The total wage bill of the EIRIN economy $Y_w = N_{high}\, w_{high} + N_{low}\, w_{low}$ is consistent with the setting of the average wage (Eq. 11). Thus, it is independent of the labor force allocation in high and low wage sectors. Instead, it only depends on the employment level. Hence, we can prove the identity Eq. 12.

$$
\begin{aligned}
w_{high} &= ((1-z)\, w_{max} + z\, w_{min} + w_{max})/2 && (9)\\
w_{low} &= ((1-z)\, w_{max} + z\, w_{min} + w_{min})/2 && (10)\\
\Delta w &= (-\theta_1 + \theta_2\, e) && (11)\\
N_{high}\, w_{high} + N_{low}\, w_{low} &= (N_{high} + N_{low})\, w && (12)
\end{aligned}
$$

Two consumption goods producers (F_L and F_K) produce an amount q_j^C of heterogeneous consumption goods by relying on a Leontief technology, since the model is applied to the short-term (e.g. up to 5 years). This implies a limited substitution of input factors (Eq. 13), meaning that if an input factor is constrained (e.g. limited access to credit to finance investments), the overall production is proportionately reduced. In contrast, several macroeconomic models allow the perfect substitution of input factors (elasticity of substitution equals 1) by using a Cobb-Douglas production technology. In our case, this would imply a perfect substitution of constrained input factors such as capital stock with labor or energy, while still generating the same level of output.

$$q_j^C = \min\left(\gamma_j^N\, N_j,\, \gamma_j^K\, K_j,\, \gamma_j^{EN}\, q_j^{EN},\, \gamma_j^R\, q_j^R\right) \tag{13}$$

with $j = F_L, F_K$. F_L is more labor intensive, meaning that $\gamma_{F_L}^N < \gamma_{F_K}^N$ but employs low-skilled workers only, receiving low wages w_{low}. F_K is more capital intensive, meaning that $\gamma_{F_K}^K < \gamma_{F_L}^K$ and employs high-skilled workers only, receiving high wages w_{high}. The two consumption good producers set their consumption goods price as a mark-up μ_j on their unit labor costs $w_j\, N_j$, unit capital costs $r_D^j\, L_j$, unit energy $p_{EN}\, q_j^{EN}$ and unit resource costs $p_R\, q_j^R$ (Eq. 14). Higher prices as a consequence of higher credit costs, more expensive imports, more expensive energy or labor costs constrain households' consumption budgets, which in turn lower aggregate demand. This represents a counterbalancing mechanism on aggregate demand.

$$p_j^C = \frac{w_j\, N_j + r_D^j\, L_j + p_{EN}\, q_j^{EN} + p_R\, q_j^R}{q_j} \tag{14}$$

The minimum between real demand of the two consumption goods and the real supply (Eqs. 16 and 15) determines the transaction amount $\widetilde{q_j}$ that is traded in the goods market. The supply of capital intensive consumption goods also takes firm's inventories (IN_{F_K}) into account. In case that demand exceeds supply, both capitalist and worker households are rationed proportionally to their demand, whereas tourism demand is prioritized. The share of newly produced but unsold products add up to the inventory stock of F_K's inventories (IN_{F_K}). Finally, both consumption goods producers make a production plan $\widehat{q_j^C}$ for the next simulation step based on recent sales and inventory levels.

$$\widetilde{q_{F_K}} = \min\left(IN_{F_K} + q_{F_K},\ \frac{C^{F_K}_{H_w} + C^{F_K}_{H_k}}{p^C_{F_K}} \right) \tag{15}$$

$$\widetilde{q_{F_L}} = \min\left(q_{F_L},\ \frac{C^{F_L}_{H_w} + C^{F_L}_{H_k} + Tu_{F_L}}{p^C_{F_L}} \right) \tag{16}$$

An energy sector (EN) that produces energy that is demanded by households and firms as an input factor, respectively for consumption and for production (Eq. 17). The energy sector in the selected developing and emerging countries requires large and persistent investments, access to credit and often benefits from government subsidized feed-in tariffs, thus being an important sector for analyzing shock transmission. Households' (H_w and H_k) energy demand is inelastic (i.e. the daily uses for heat and transportation). Firms' energy requirements depend on the sectors' market share in the economy and on the overall economic business cycle. The energy company requires capital stock and oil as input factors for production. The energy price is endogenously set by the energy firm and based on a mark-up μ^{EN}, on its unit capital $r^{EN}_D\, L_{EN}$ and unit oil price $p_O\, q_O$ costs (Eq. 18). The oil price p_O is assumed to be determined in international markets and thus is modelled as an exogenous variable characterized by a constant growth rate μ_o. H_w and H_k subtract the energy bill from their wage bill as shown by their disposable income (Eq. 4). Industry transfers the costs of energy via mark-ups on its unit costs to their customers (Eqs. 14 and 23). To be able to deliver the demanded energy, the energy producer requires capital stock. EN conducts investment to maintain depreciated capital stock and expand its capital stock to be able to satisfy energy demand.

$$q_{EN} = q^{EN}_{H_w} + q^{EN}_{H_k} + q^{EN}_{F_L} + q^{EN}_{F_K} + q^{EN}_{K} \tag{17}$$

$$p_{EN} = (1 + \mu_{EN}) \left(\frac{r^{EN}_D\, L_{EN} + p_O\, q_O}{q_{EN}} \right) \tag{18}$$

Endogenous investment decision. Both consumption good producers (F_L and F_K) make investments based on the expected production plans $\widehat{q^C_j}$ that determine a target capital stock level $\bar{K}_j$. As a difference from supply-led models (e.g. Solow (1956)), the investment decision is fully endogenous and it is based on firms' Net Present Value (NPV). This in turn is influenced by six factors, i.e (i) investment costs, (ii) expected future discounted revenue streams (e.g. endogenously generated demand), (iii) expected future discounted variable costs, (iv) the sector dependent interest rate by the commercial bank, (v) the government's fiscal policy and (vi) governments' subsidies. The NPV calculations allow us to compare the present cost of investments with the present value of future expected (positive or negative) cash flows (Eq. 21). In particular, we can distinguish four cash flows. A positive cash flow is given by the additional sales due to investment. Three negative cash flows include: the additional labor costs required to match the need for increased production capacity; the additional raw materials costs incurred to produce the additional output; extra energy requirements for producing additional output. The energy firm relies on capital and on oil as production inputs, and considers the costs of using additional oil units for an additional unit of output. This formulation allows us to understand agents' intertemporal behavior by comparing the short-term costs of investments with their long- term benefits. The sign of the NPV determines whether the agent makes the decision. The planned investment amount is set by the target capital level $\bar{K}$ considering the present capital endowment K_n subject to depreciation $\delta\, K_n$ and potential capital destruction as a consequence of natural disaster shocks ξK_n (Eq. 19). The implementation of the target investment plan is then potentially constrained by the firms' available liquidity, i.e. M_n, plus the possibility to take new debt $\Delta\, L_n$ with the bank given a constraint on the maximum allowed leverage α_n (Eq. 20).

$$\hat{I}_n = \max\left(\bar{K}_n - (1 - \delta\, K_n) - (1 - \xi\, K_n)\,, 0\right) \quad (19)$$
$$I_n \leq M_n + \Delta L_n \quad (20)$$
$$NPV_j = -p_K\, I_j + \sum_{t=1}^{+\infty} \left(\frac{\Delta\, \widehat{q_j^C}\, p_j - w_j\, \Delta\, N_{j,t} - \Delta q_j^R\, p_R - \Delta\, q_j^E\, p_{EN}}{(1 + r_D^j)^t} \right) \quad (21)$$

where I_j represents real investments in new capital goods; p_K is the present price of capital goods; $\Delta\, \widehat{q_j^C}$ is the additional expected production (and sale) due to investments; p_j^C is the expected consumption goods sale price at the next t-th simulation step; r_D^j is the present sector dependent loan interest rate on debt set by the commercial bank; w_j is the salary paid to workers in the consumption goods production sectors; ΔN_j is the additional amount of workers required at the next t-th simulation step to match the additional production capacity due to investments; p_R is the expected raw materials price at the next t-th simulation step; Δq_j^R is the additional amount of raw materials required at the next t-th simulation step to match the additional production capacity due to investments; p_{EN} is the expected energy price at the next t-th simulation step; Δq_j^{EN} is the additional amount of energy required at the next t-th simulation step to match the additional production capacity due to investments.

A capital goods producer (K) that produces capital goods to fulfill the production capacity of consumption goods producers and of the energy firm (Eq. 22). The capital good producer relies on energy and high-skilled labor as input factors that represent its unit costs. Capital good price p_k is set as a fixed mark-up μ_k on unit costs (Eq. 23). Newly produced capital goods will be delivered to the consumption good producers and the energy firm at the next simulation step.

$$q_K = I_{F_L} + I_{F_K} + I_{EN} \quad (22)$$
$$p_K = (1 + \mu_K) \left(\frac{w_{high}\, N_K + q_K^{EN}\, p_{EN}}{q_K} \right) \quad (23)$$

A financial sector composed of a commercial bank that sets sector specific interest rates for loans granted. The commercial bank endogenously creates money (Jakab & Kumhof, 2015), meaning that it increases its balance sheet at every lending (i.e. the bank creates new deposits as it grants a new credit). This is consistent with most recent literature on endogenous money creation by banks (McLeay et al., 2014).

A central bank sets the policy rate based on the Taylor rule. A sovereign bonds market determines the price and spreads for sovereign bonds by balancing demand and supply.

The commercial bank provides loans to the two consumption good producers and the energy firm. The EIRIN economy money supply is displayed by the level of demand deposits. These include the deposits of worker and capitalist households, of the consumption and production sectors, of the energy firm as well as of government. Further, BA gives out loans to finance firms' investment plans. Depending on the firm's leverage ratio of outstanding debt to equity $\frac{L_n}{E_n}$, BA sets sector specific interest rates (Eq. 25) that affect firms' capital costs and NPV decision. The maximum credit supply of the bank is set by its equity level E_{BA} divided by the Capital Adequacy Ratio (CAR) parameter, in order to comply to banking regulator provisions. The additional credit that the bank can provide at each time step is given by its maximum supply, minus the amount of loans already outstanding (Eq. 26). Thus, credit demanded by firms may be rationed due to insufficient equity capital on the bank's side. In case of rationing, credit is allocated proportionally to the demand schedules of the two consumption good firms and of the energy firm, and the effective credit received ΔL_n may be lower than the amount demanded. Therefore, the consumption goods firms and the energy firm can be rationed in the credit market. In case of credit rationing, firms have to scale down their investment plans, while the bank stops paying dividends in order to increase its equity capital.

$$r_D^{n,T} = r_{D,t-1}^n \left(1 + \left(\frac{\frac{L_n}{E_n} - \psi}{\psi}\right)\right) \tag{24}$$

$$r_{D,t}^n = r_{D,t-1}^n + \lambda_r \left(r_D^{n,T} - r_{D,t-1}^n\right) \tag{25}$$

$$\Delta L_n \leq \max\left(\frac{E_{BA}}{C\bar{A}R} - L_{n,t-1}, 0\right) \tag{26}$$

where $r_{D,t-1}^n$ is the previous period sector-specific interest rate; $\frac{L_n}{E_n}$ is the n-firm's debt to equity ratio; ψ is a target debt to equity ratio BA considers to be acceptable without additional risk premium, $r_D^{n,T}$ is a target interest rate, while λ_r is an adjustment speed parameter, considering the fact that BA cannot achieve their target rate immediately.

A foreign sector (RoW) composed of: migrants' remittances sent to both households; tourism (Tu_{C_l}); raw materials ($p^{EN} q_X^{EN}$), consumption good exports ($p_L^C q_L^C$) and intermediate good exports ($p_K^C q_K^C$); development finance (grants or loans) (L_{ROW}); consumption good imports ($q_{Hm} p_{Rc}$); oil ($p_O q_O$) and raw materials supply ($p_R q_R$) to the domestic economy. These latter are provided in infinite supply and at a given price to meet the internal production needs. Tourists inflows consist in the consumption of labor-intensive consumption goods. Remittances are implemented as monetary flows from the foreign sector to the worker and capitalist households. Development finance is implemented as a monetary flow to the government. Raw material, consumption good and intermediate good exports are a calibrated share of the country's GDP and are sold at world prices. Tourism sector demand, remittances and development finance's amount and growth rate are defined via exogenous parameters. This allows us to assess the indirect impact of COVID-19 health crisis on the country's economy. The impacts are negative in the case of tourism and remittances and affect the exports of raw materials, consumption goods and intermediate goods via price or demand shocks. In this way we channel shocks from the global markets to the EIRIN economy. In contrast, the impacts are positive or neutral in the case of development finance inflows to face the COVID-19 crisis.

A government (G) that is in charge of implementing the fiscal policy, via tax collection and public spending, including welfare expenditures, subsidies (e.g. for households' consumption of basic commodities), public sectors' workers and consumption. To cover its regular expenses the government raises taxes and issues sovereign bonds, which are bought by the capitalist households, by the commercial bank and by the central bank. The government pays coupons on its outstanding bonds ($n_G\, c_B$) and interest on loans granted by multilateral development finance institutions ($r_{ROW}\; Loans_{ROW}$). Taxes are applied to labor income (wage), to capital income (dividends and coupons), and profits of firms. To meet its budget balance target level, the government adjusts its tax rate. In case of a budget deficit, the tax rate is increased by a fixed amount $\Delta\,\tau$. In case of a budget surplus exceeding a given threshold, the tax rate is decreased by the same fixed amount $\Delta\,\tau$. Otherwise, the tax rate τ is kept constant. Furthermore, if the government's deposits are lower than a given positive threshold $\bar{M}$, i.e., $M_G < \bar{M}$, the government issues a new amount $\Delta\, n_B$ of bonds to cover the gap:

$$\Delta\, n_B = \frac{\bar{M} - M_G}{p_B} \tag{27}$$

where p_{bond} is the endogenously determined government bond price. All newly-issued brown bonds are bought by the capitalist households, the commercial and the central bank. Government spending plays a complementary role during crises to avoid a credit crunch and compensate households' and firms' liquidity constraints (Brunnermeier et al., 2020). Government spending is given by a fixed percentage of revenues deriving from tax collection:

$$G_c = \kappa\, R_G \tag{28}$$

where R_G represents the government revenues and κ is an exogenous parameter.

A Central Bank (*CB*) that sets the interest rate according to a Taylor like rule. The interest rate in EIRIN indirectly affects households consumption via price increase stemming from firms that adjust their prices based on higher costs for credit. Households have a target level of wealth stemming from buffer-stock saving (s.above) but do not inter-temporally maximize their consumption behavior. This prevents monetary policy to have a crowding-out effect on household consumption. The policy interest rate depends on the inflation ($\pi - \bar{\pi}$) and output gaps (measured as employment gap ($u - \bar{u}$) (i.e. the distance to a target level of employment $\bar{u}$)) and influences agents' expectations and investments through the NPV. In particular, π is the inflation of the weighted average of consumption goods prices (Eq. 30) between two consecutive simulation steps. The inflation gap is computed as the distance of the actual inflation π to the target inflation rate $\bar{\pi}$. The unemployment rate u is computed in Eq. 31 as the fraction of people employed in the capital good and the two consumption good producers of the overall labor force N_{tot}. Eq. 32 constitutes the employment rate. Further, the CB can also provide liquidity to BA in case of shortage of liquid assets.

$$r_{CB} = \omega_\pi(\pi - \bar{\pi}) + \omega_u(u - \bar{u}) \tag{29}$$

$$\pi = \frac{q^C_{F_L}}{q^C_{F_K} + q^C_{F_L}} \frac{\Delta\, p_{F_L}}{p_{F_L}} + \frac{q^C_{F_K}}{q^C_{F_K} + q^C_{F_L}} \frac{\Delta\, p_{F_K}}{p_{F_K}} \tag{30}$$

$$u = 1 - \frac{N_K + N_{F_L} + N_{F_K}}{N_{tot}} \tag{31}$$

$$e = \frac{N_K + N_{F_L} + N_{F_K}}{N_{tot}} \tag{32}$$

3. Model dimensioning and calibration

Mexico is a middle-income country in North America. The country is the 11th largest economy in the world, but characterized by huge regional disparity and unequal income distribution, with 46% of the population living below the poverty line (The World Factbook, 2020). The economy is highly integrated into the global value chain, where a large industry and manufacturing sector (31% of 2018 GDP, (The World Bank, 2020b)) produces goods for global export markets ranging from agricultural products to intermediate and final consumption goods in the automotive, computer and electronic industries (Atlas of Economic Complexity, 2020). As such, Mexico strongly depends on international trade and foreign direct investment (FDI), with Mexico's exports constituting 39%, imports 41% and net FDI inflows being 3.1% of its 2018 GDP (The World Bank, 2020b). The USA plays an important role as economic partner for Mexico, being its major customer country (76% of its exports, (WITS, 2020)). Furthermore, several Mexican citizens work in the USA and send back remittances, which constitute 3% of GDP, but with $37bn, being by far the highest recipient of absolute remittances flows in the region (The World Bank, 2020b). Tourism is also an important economic sector (2% of 2018 GDP), especially for certain regions in the country that lack other sources of income. This strong dependence on external demand meets a slowing down economy (due to trade disputes with the Trump administration) and high inflation (6% as 5 year average), where the government has limited fiscal space, with debt to GDP ratios of 46% of GDP in 2018 (Trading Economics, 2020) and limited access to capital markets.

Those structural characteristics of the Mexican economy make it especially vulnerable to external demand shocks that come along with the spread of the COVID-19 epidemics and thus a proper case study to our quantitative compound COVID-19, climate change and financial risk assessment.

3.1. Model calibration

First, we replicate the main structural macroeconomic and financial characteristics, by adapting the EIRIN model structure (Monasterolo & Raberto, 2018, 2019) to Mexico. To do so, we collected and analysed the main macroeconomic data and features of the economies using statistical information provided by the World Bank database of world economic indicators (The World Bank, 2020b)[1]; COVID-19 data from John Hopkins COVID-19 tracker (John Hopkins University, 2021); and COVID-19 policy response information (on fiscal and monetary policy) provided by the IMF COVID-19 policy tracker (IMF, 2020). In particular, the data showed the importance that export, tourism and remittances' flows from abroad play in Mexico as sources of aggregate demand and household income.

Second, we initialize the model to a quasi steady-state in which the core variable ratios and growth rates are stable. We dimension the simulated economy to quantitatively mimic the main macroeconomic growth rates and ratios of the country under investigation via core model parameter settings. We opt for this indirect inference strategy due to limited availability of detailed macroeconomic data for the countries of analysis. The model's accounting structure represented by a balance sheet, a transaction flow and a net worth matrix (see Appendix A) further ensure the internal model consistency. We present our results by comparing model's indicator means with observed data

[1] Due to data gaps we relied for 2018 data on Mexico's debt to GDP ratio on Trading Economics (2020) and Mexico's tourism to GDP ratio on Statista (2020)

means during a time span of 5 years. Further, we present the EIRIN model flows at the beginning of the simulation period in a Sankey diagram, showing the dimensioning of the macroeconomic flows of Mexico.

The two strategies help us to justify our parameter choices in an interactive and dynamic process, which goes through multiple rounds of testing, and to increase the validity of our results. This allows us to draw evidence-based policy-relevant conclusions on the impact of compound COVID-19, climate-led natural hazards and financial risks onto the selected countries.

As such, our study contributes to a methodological advancement of systemic macrofinancial risk assessment of compound events, while providing insights on weak-spots relevant for increasing resilience to compound COVID-19, financial and natural hazard risk in low- and middle-income countries.

In particular, the calibration and dimensioning exercise focuses on:

- Macroeconomic indicators (e.g. real GDP growth rate)
- Sectors' value added
- Relations between the domestic economy and the foreign sector (e.g. remittances and export).

We first calibrate the main macroeconomic indicators, represented by the GDP growth rate, inflation and unemployment rate. They are shown in Table 1.

Variable name	**Mean of simulated values**	**Standard deviation of simulated values**	**Mean of real values**	**Standard deviation of real values**
Real GDP growth rate	2.13%	0.02%	2.06%	1.33%
Unemployment rate	3.8%	0.11%	3.66%	0.42%
Inflation rate	3.34%	0.01%	4.02%	1.43%
Government debt (% of GDP)	48.31%	0.71%	45.94%	1.51%
Government spending (% of GDP)	12.18%	0.02%	11.85%	0.32%

Table 1: The table reports the mean and standard deviation computed both on simulated and on real variables of Mexico for a time span of 5 years.

After dimensioning the main macroeconomic indicators, we proceed with a more detailed comparison by considering the sectors' value added, as shown in Table 2. EIRIN includes two different consumption goods producers, one more labor intensive and the other more capital intensive. We identify the labor intensive sector with the service sector and the capital intensive sector with the industry sector.

The last set of variables considered in the dimensioning exercise include the indicators related to

Variable name	Mean of simulated values	Standard deviation of simulated values	Mean of real values	Standard deviation of real values
Value Added of industry sector, including manufacturing (% of GDP)	30.46%	0.08%	30.28%	0.59%
Value Added of service sector (% of GDP)	63.18%	0.13%	63.92%	0.32%

Table 2: The table reports the mean and standard deviation computed both on simulated and on real variables of Mexico for a time span of 5 years.

the relation of the domestic economy with the rest of the word, i.e. remittances, tourism, import and export (Table 3).

Variable name	Mean of simulated values	Standard deviation of simulated values	Mean of real values	Standard deviation of real values
Remittances (% of GDP)	3.2%	0.02%	2.74%	0.32%
International tourism (% of GDP)	8.75%	0.06%	8.68%	0.11%
Import (% of GDP)	41.04%	0.29%	39.08%	1.63%
Export (% of GDP)	40.06%	0.26%	37.53%	1.9%

Table 3: The table reports the mean and standard deviation computed both on simulated and on real variables of Mexico for a time span of 5 years.

3.2. Sankey plot of the Mexican economy

We display the simulated cash flows at the beginning of the simulation run (i.e., before the different scenario shocks) with a Sankey plot to ensure that the flows of the EIRIN model are consistent with its accounting framework (Figure 3.1). The Sankey plot provides a visual representation of the distribution and proportionality of inflows and outflows among EIRIN's agents and sectors, consistently with the model initialization and calibration.

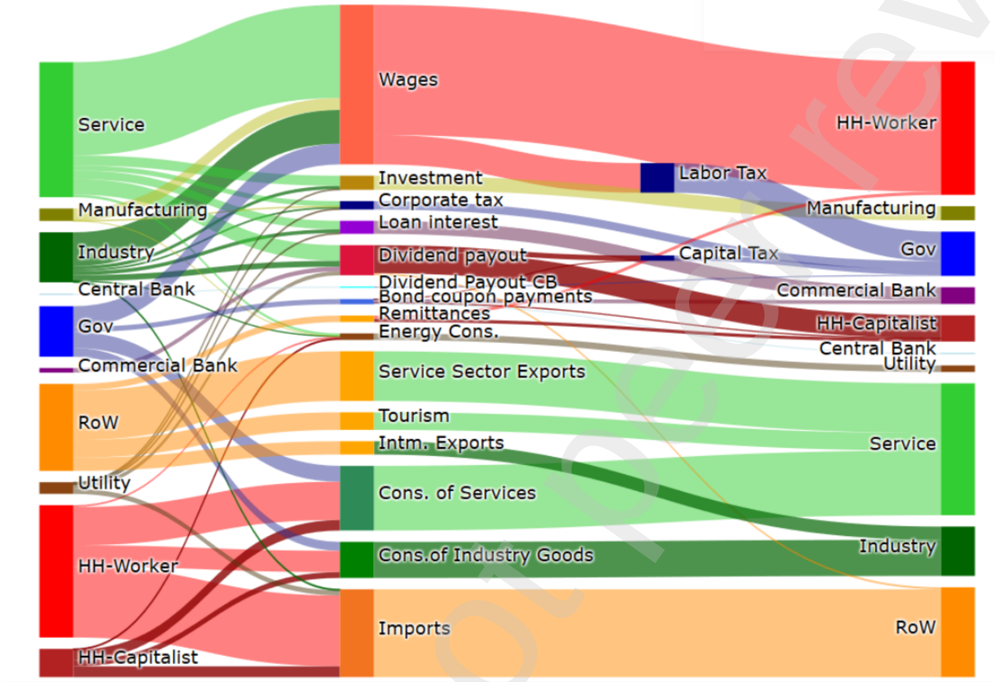


Figure 3.1: **Sankey plot of the EIRIN economy**: The Sankey plot represents all current account outflows and inflows of EIRIN's agents and sectors at the beginning of the policy simulation. Left and right side of the figures include the main agents and sectors of EIRIN tailored to the Mexican economy. Central part of the figure represents the use of the monetary flows. How to read the Sankey plot: moving from the left to the right side we capture, respectively, the outflows to the use and the inflows from the use to the agents and sectors. Unit of measurement: $ US Dollars. The service sector hereby represents the labor-intensive consumption good sector, industry the capital-intensive consumption good sector and manufacturing the capital good sector in the EIRIN model.

4. Scenarios

4.1. COVID-19

COVID-19 has a large negative socio-economic impact on Mexico. Numbers of infections (2,280,213) and COVID-19 related fatalities (209,338) are high (John Hopkins University, 2021), despite government containment measures (e.g. curfew, border restrictions). In turn, domestic consumption was estimated to decrease by 8.3% in 2020 (OECD, 2020). Further, external shocks were expected to be significant for Mexico. Exports (in particular of cars, electronics and intermediate goods), constituting 39% of the Mexican economy, were expected to drop by 9.2% in 2020 (OECD, 2020). International tourism were expected to drop by 50% in 2020 in Mexico due to travel restrictions all over the world (UNWTO, 2020). Finally, remittances, making up 3% of Mexican GDP, were expected to drop by 19.3% in 2020 (The World Bank & KNOMAD, 2020) due to economic downturns in the host countries (especially in the USA). The Mexican government responded with fiscal measures to mitigate the negative socio-economic impacts of the COVID-19 outbreak. The measures specifically include health, private household support and business liquidity and guarantee measures, equal to 1.2% of 2019 GDP (IMF, 2020). The central bank of Mexico also took a supportive role by lowering its policy rate by 250 basis points and implementing monetary policy measures of an equivalent of 3% of 2019 GDP to ensure financial stability and sufficient market liquidity (IMF, 2020).

We include both the international and domestic drivers of economic shocks in our simulations, as well as the government response measures within the COVID-19 scenarios (see Section 5.2 for an analysis of the results). Further, as a main objective of this study, we assess the effectiveness of government fiscal and monetary response measures in a given scenario situation in varying degrees (see Section 5.3 for an analysis of the results).

4.2. Climate disaster risk assessment

Climate physical risk: Hurricanes are a major cause of economic losses in Mexico, representing more than 40% of the country's economic losses due to climate related hazards (Guha-Sapir et al., 2009; UNISDR, 2021). Historically, Hurricane Wilma in 2005 is the most significant event in terms of damages and losses ever recorded in Mexico, with direct damages estimates in the order of USD 500 million and total economic losses around USD 1.3 billion, most of which affecting the tourism sector of Quintana Roo state (CENAPRED, 2006).

Overall, the magnitude of the direct damages due to hurricanes mainly occur due to wind destruction and flooding, the later as a consequence of storm surge events in coastal areas. Those processes are strongly strongly dependent on the maximum sustained wind speeds experienced at ground levels (Ishizawa et al., 2019). To estimate the potential destruction of capital stock in Mexico, we rely on the use of a hurricane damage function proposed by Emanuel (2011) that accounts for three main features: i) damages are accounted for only when sustained winds speeds are larger than a specified minimum threshold; ii) damages vary as the cube of the sustained wind speed over a threshold value, and; iii) the damage potential approaches unity at very high wind speeds, and it cannot exceed unity in any event. The formulation employed is shown Eq. 33 (Emanuel, 2011):

$$F_{index} = \frac{v^3}{1+v^3} \qquad (33)$$
$$v = \frac{\max((W_{spd} - W_{thresh}),0)}{W_{half} - W_{thresh}}$$

Here, the damage function allows to translate wind speed into direct damages to capital stock via the cubic power of wind speed on the physical grounds, defining a lower bound threshold W_{thresh} of no damage occurrence and a threshold W_{half}, where half of the damages occur. In order to apply such a function to the Mexican reality, we use open-access data from EM-DAT disaster risk data base 2020, covering the past 30 years (1990-2020), to calibrate the above-mentioned damage function for the assessment of hurricane risk in Mexico. We consider the range of possible values for W_{half} as discussed in Emanuel (2011) and Ishizawa et al. (2019), keeping those between 225 and 320 km/h, while also using as initial value of W_{thresh} the value of 92km/h, as in Emanuel (2011). We estimate W_{thresh} to be 65 km/h and W_{half} to occur at a wind speed value of 253 km/h.

The damages from hurricane events are also strongly dependent on their landfall area. For instance, 2004 is a year that ranks among the costliest Atlantic hurricane seasons, while Mexico was barely hit during that season; in contrast, 2007 was a slightly above-average Atlantic hurricane season, not being ranked among the costliest hurricane seasons, yet hurricane Dean caused major damages in Mexico in the order of USD 180 million. In order to quantify the potential direct damages to capital stock, we perform a probabilistic risk assessment of direct hurricane damages in Mexico. Probabilistic wind speed data is obtained from UNEP-GRDP database on tropical cyclones and hurricanes (Cardona et al., 2015; UNISDR, 2015). The UNEP-GRDP database on tropical cyclones provides a series of probabilistic wind hazard maps at 0.25° resolution and for the return periods of 1 in 50, 1 in 100, 1 in 250, 1 in 500, and 1 in 1000 years. Wind speed data is provided as 3-seconds gusts over the surface, hence being converted to sustained wind speed following the methodology proposed by Harper et al. (2010). We account for the return period of 1 in 10 years by interpolation wind speed data from the available expected frequencies using a logarithmic regression function fitted independently for each spatial cell. We then calculate the damage index factor, F_{index}, to obtain the relative losses with respect to different levels of sustained wind speed, as in Eq. 2 ranging between 0 and 1. Results are shown in Figure 4.1.

Country-wise, considering the above mentioned probabilistic approach, we estimate that a mild-impact hurricane (i.e. 1 in 50-year event) results in the destruction of 0.43% of the productive capital stock in Mexico, while a large-impact natural hazard shock (i.e. 1 in 100-year event) destroys 0.98% of the productive capital stock (see Section 4.2 for details).

Being Mexico a large country with a diversified economy and heterogeneous distribution of population and assets, the country is heterogeneously exposed to hurricane hazard. In order to select the most relevant economic and touristic states in Mexico in terms of exposure to hurricanes (see Table 4), we first obtain Mexican state-level GDP from the Mexican Statistical Institute (2020). Then, we identify the Mexican state-level that are subject to hurricane events by analysing the probabilistic wind speed data is obtained from UNEP-GRDP database on tropical cyclones and hurricanes (Cardona et al., 2015; UNISDR, 2015). Finally, the relative contribution of those states to total Mexican GDP is used to rank potential damages to those economic and touristic important states in Mexico. As a result, we identify the cities of Mexico City, Cancun (Quintana Roo), Aca-

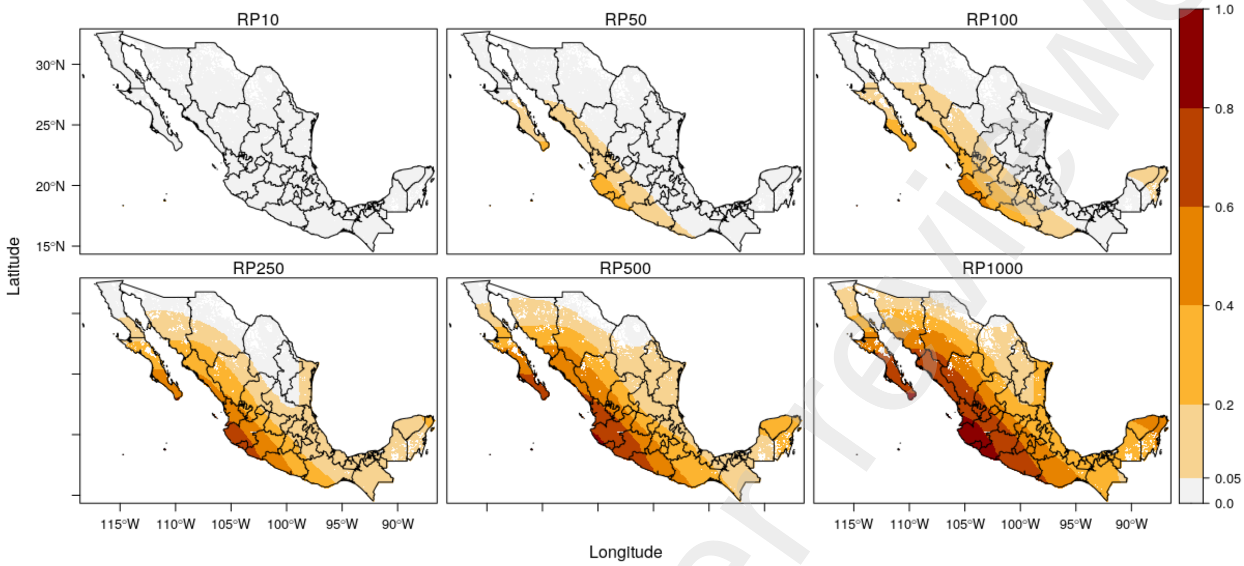


Figure 4.1: Damage index factor, Findex, computed for six different hurricanes return periods in Mexico based on UNEP-GRDP data (Cardona et al., 2015; UNISDR, 2015)

State	**Role for Country**	**Share of Total Mexican GDP**	**RP 1-50 year**	**RP 1-100 year**
Mexico City	Capital, Most important cultural, political and economic city in Mexico	17.67%	1.09%	3.2%
Quintana Roo	Tourism	1.62%	0.25%	0.44%
Guerrero	Tourism	1.36%	0.47%	0.68%
Oaxaca	Tourism	1.476%	0.12%	0.3%
Nuevo Leon	Industrial Production	7.65%	0.01%	0.11%
Coahuila	Industrial Production	3.44%	0.00%	0.04%
Jalisco	Electronic and Textile Industry	6.82%	1.47%	2.86%
Campeche	Mining	2.99%	0.03%	0.19%
Sum		**43%**	⌀0.43%	⌀0.98%

Table 4: Selected state contribution and damages for a mild (R 1-50 year) and strong (R 1-100 year) hurricane in Mexico

pulco (Guerrero), Huatulco (Oaxaca), Monterrey (Nuevo Leon), Saltillo (Coahuila), Guadalajara (Jalisco), and San Francisco de Campeche (Campeche) as particularly exposed to hurricane hazard Mexico.

The direct impacts from hurricanes are just one facet of the total damages from this kind of extreme weather events. Indirect damages often follow after a hurricane makes a landfall over populated area. Those are mainly due to business interruption, the shutdown of touristic attractions and the cancellation of touristic reservations, ultimately leading to lower productivity and increased unemployment. Indeed, for hurricane Wilma for instance, more than 60% of the total damages are attributed to indirect losses (CENAPRED, 2006). In order to capture the channeling of direct damages into indirect losses due to hurricanes in the identified cities in Mexico, we shock the EIRIN model with the estimated relative productive capital stock destruction, as shown in Table 4). Those shocks are assumed to occur in the fourth quarter of 2020, as the hurricane season in Mexico usually lasts from the end of June until the end of November[2], hence consistently with the hurricanes season in the country.

We design four scenarios (Figure 4.2) that allow us to isolate the effects of COVID-19 and climate physical risks (i.e. a hurricane hazard) on the Mexican economy and public finance and to assess impact changes, when those risks compound. We consider two different dimensions of the COVID-19 and hurricane hazard shock. First, both shocks occur as individual events or in sequence. Second, the shock size of the hurricane hazard could vary, inducing mild or strong impacts on the productive capacity of firms in the EIRIN economy. Giving the current lack of data, we base the COVID-19 scenario impact assumptions for Mexico on estimates from a several official data sources. Impacts include exports (-9.19%), remittances (-19.3%), tourism (-50%) and domestic consumption reductions (-8.26%). COVID-19 fiscal and monetary response measures are taken from the IMF Policy Tracker. We then compare scenario outcomes to a business as usual (BAU) scenario, where no shocks occur. In addition, we assess the relevance of government's fiscal measures for economic recovery (see Section 5.3), considering varying levels of government spending during the crisis ΔG. We contrast results with constraining factors such as bank's credit supply (CAR), showing the relevance of financing conditions and access to credit in the disaster aftermath.

5. Results

5.1. Risk transmission channels

We first identify the most relevant climate physical risks (i.e. hurricanes, blue) and the COVID-19 (red) transmission channels to the real economy and banking sector of Mexico (Figure 5.1), which we then quantitatively assess with the EIRIN model. The analysis of risk transmission channels is crucial to identify the shocks' entry points, the direct and the indirect impacts in the economy, public and private finance, given the type of shock and country's characteristics. Our analysis of the climate risk transmission channels stands on a body of recent literature (Battiston et al., 2017; Battiston & Monasterolo, 2020; Gallagher et al., 2021; Semieniuk et al., 2021; Volz et al., 2020).

Hurricanes enter the economy by destroying productive capital, which impacts firms' production (direct impact), as it requires capital as an input factor. Hurricanes represent a supply shock that

[2] NOAA (2020)

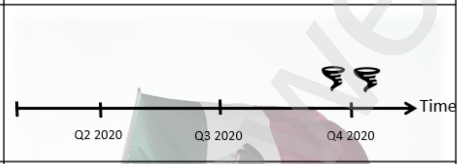
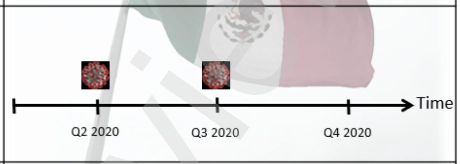
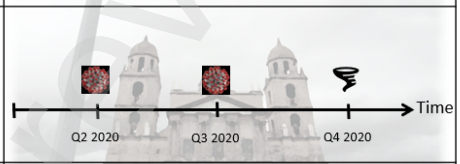
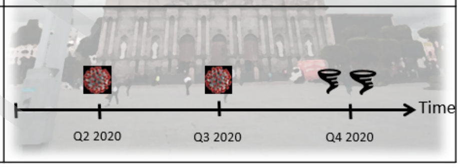
Scenario No	COVID-19 Lockdown and Policy-response measures	Natural Hazard Occurrence	Graphical Representation
1 Strong hazard	No	Timing: Q4 2020 Impact Size: ς_H = 0.98%	
2 COVID-19 emergency	**Impact from RoW:** • Remittances: **-19.3%** (World Bank & KNOMAD) • Tourism: **-50%** YTD (June 2020) UNWTO • Exports: **-9.19%** (OECD Economic Outlook Double Hit Scenario September 2020) **Impact from domestic economy:** • Private consumption: -**8.26%** (OECD Economic Outlook Double Hit Scenario September 2020) **Gov response measures** (IMF) : *Fiscal:* • Government support increase: **1.2%** of 2019 GDP *Monetary* • Policy rate reduction by **250bps** • Measures to support the financial system: **3.3%** of 2019 GDP	No	
3 Compound COVID-19 and mild hazard		Timing: Q4 2020 Impact Size: ς_L = 0.43%	
4 Compound COVID-19 and strong hazard		Timing: Q4 2020 Impact Size: ς_H = 0.98%	

Figure 4.2: **Compound COVID-19 and climate risk scenarios**: Affected sectors by COVID-19 and natural hazard occurrence and respective shock sizes.

limits firms' ability to serve demand. In the short run, firms cannot easily substitute capital as an input factor, laying-off people. This increases unemployment, which directly affects household income and indirectly weakens workers' wage bargaining power, lowering household consumption and real GDP. Note that sectors are affected differently by the hurricane shock, allowing the capital goods production sector to use unused capacity to serve the additional investment demand.

COVID-19 originates as a demand shock to the economy. External demand from tourism, remittances and exports is reduced due to global travel restrictions and lower economic growth globally. Internal demand, especially domestic private consumption, falls as a consequence of lockdown and curfew measures. The contraction in external and domestic demand negatively affects firms' production. Consequently, unemployment increases, household consumption decreases and real GDP falls. The COVID-19 shock indirectly impacts public and private finance. Public finance: lower tax revenues due to lower real GDP, leading to increases in government deficit, which requires the issuance of new public debt to finance the COVID-19 spending. Lower GDP and higher sovereign debt move government debt to GDP ratio upward and thus the cost of refinancing on international markets. This, in turn, reduces government's future fiscal space and its ability to react to the crisis.

Private finance: negative economic conditions increase firms' leverage ratios and higher risk of default. As a consequence, banks tighten credit conditions to firms, increasing capital costs. A wide range of investment projects become unprofitable, with negative implications on firms' new investments.

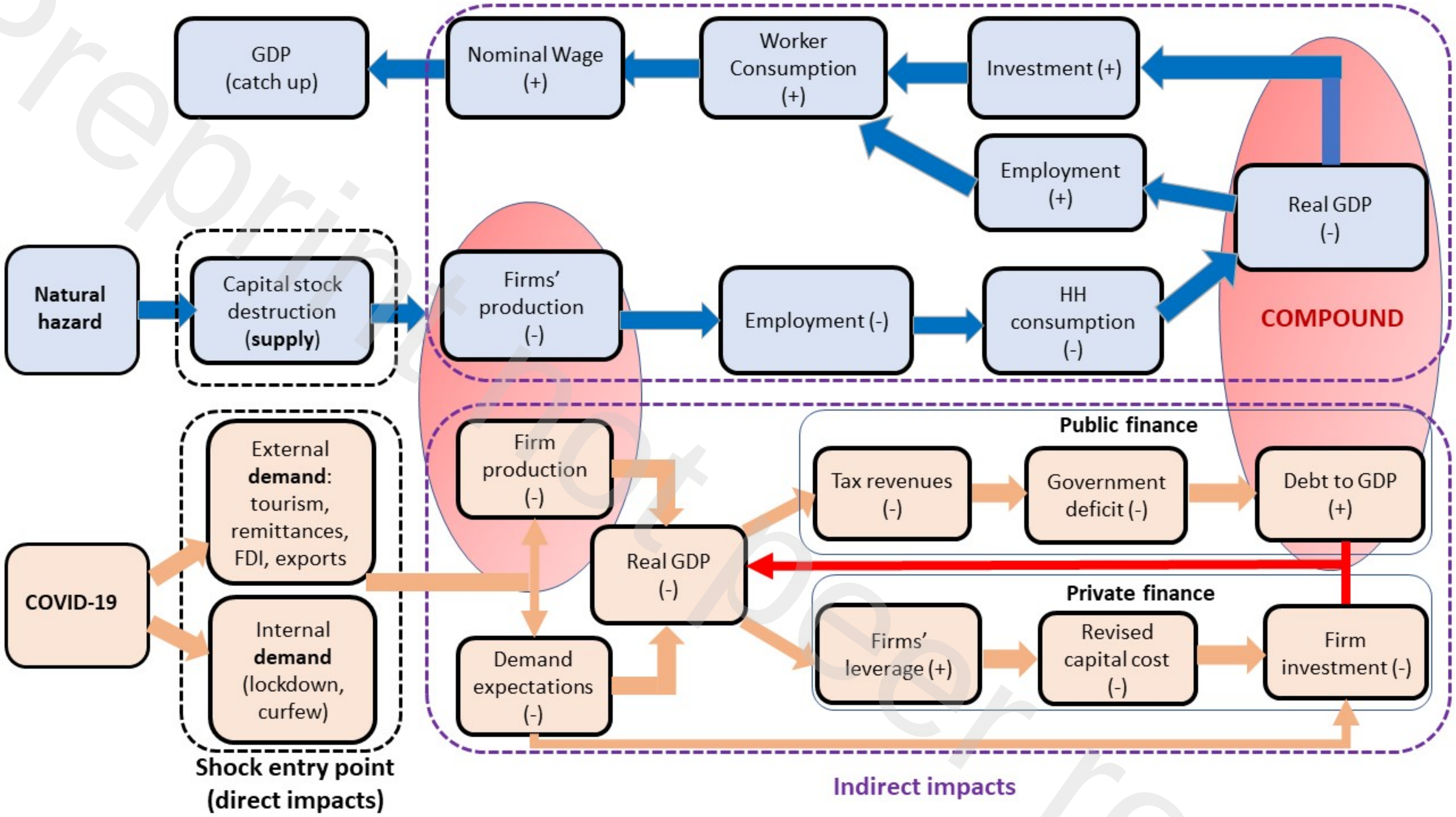


Figure 5.1: **Individual and compound risk transmission channels**. The figure shows the COVID-19 and hurricane's entry points (black dotted boxes) and transmission channels to the main variables of the real economy, public and private finance. Direct impacts correspond to the input shocks considered and are identified by the black dotted boxes, while indirect impacts are identified by the purple dotted box. The red arrow shows the reinforcing feedback loop, while the shaded red areas identify the compound effect. The signs (+/-) indicates the direction of the impact (+: variables move in the same direction; -: variables move in opposite directions, i.e. an increase in A leads to a decrease in B). The COVID-19 shock affects domestic and international demand (export, tourism, remittances), while the hurricane affects the supply by hitting firms' production. The shocks then are transmitted in the economy via real and financial flows.

5.2. Simulation results: macroeconomic indicators

In this section we present the results of our assessment of compound risk on main macroeconomic indicators of the Mexican economy (see Figure 4.2 for details)[3].

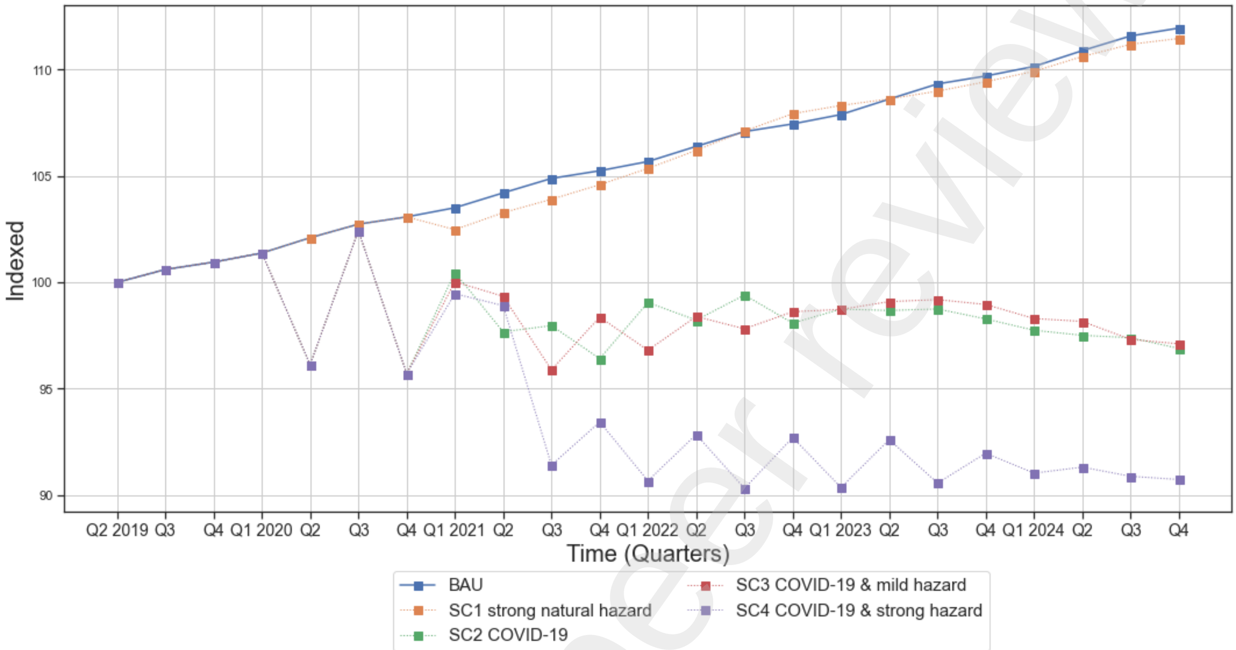


Figure 5.2: **Real GDP** (5 years time span). The x-axis shows the timeline of the simulation lasting until the fourth quarter of 2024 on a quarterly basis. The y-axis shows real GDP for Mexico indexed against the 2019 pre-shock value (GDP 2019 = 100)

A singular hurricane hazard (SC1) destroys productive capital stock, entering the EIRIN economy as a supply shock. The temporary shortage of production capacity negatively affects GDP (Figure 5.2). Since domestic and foreign demand are high when the hurricane hits, firms face a shortage in production capacity to fulfill aggregate demand. The high demand fuels firms' investment in reconstruction investments to rebuild damaged plants, offices and warehouses. This allows the economy to quickly recover and GDP is catching up with the BAU GDP levels.

In contrast, the COVID-19 crisis (SC2) induces a demand shock, leading to lower domestic consumption, tourism and exports as a consequence of global lockdowns, that strongly hit the export-dependent Mexican economy. Those direct impacts induce cascading effects in the economy via unemployment (Figure 5.3a). The cost of government response measures, including new debt (and thus the cost of debt service) in combination with lower real GDP lead to a higher public debt to GDP ratio (Figure 5.3b). The increase in government bond issuance to finance the COVID-19 response measures reduces the bond price. Lower bond prices and higher sovereign bond yields, in combination with shrinking tax revenues and higher government spending, contribute to increase the government deficit. In turn, the impact of the original COVID-19 shock is prolonged.

[3]To improve the understanding of the shock impacts, all macroeconomic indicators are indexed against the 2019 scenario value. This implies that the 2019 value in the graph will be always shown as 100. The model is initialized by the model calibration (see Section 3.1)

When COVID-19 compounds with the hurricane (SC3 and SC4), the interaction of demand and supply side shocks leads to non-linear amplification of direct impacts on GDP. This is captured by the compound risk indicator (Figure 5.8). Firms revise future demand expectations and consequently cut investments, reducing aggregate supply because no additional capacity is needed to serve demand. Unemployment increases, wages fall due to the Philipps curve dynamics, and the public debt to GDP ratio increases.

Thus, when COVID-19 compounds with hurricanes (SC3 and SC4), we note that:

- The catching-up effect in the natural hazard scenario (SC3) occurs in presence of mild hurricane damages (compared to the COVID-19 scenario). In contrast, a strong hurricane prevent the economy from catching-up (SC4).
- There is an amplification of the effect of the strong natural hazard compounding with COVID-19 (SC4) compared to the natural hazard only scenario (Figure 5.2), highlighting the existence of non-linearity of impacts (Figure 5.8).

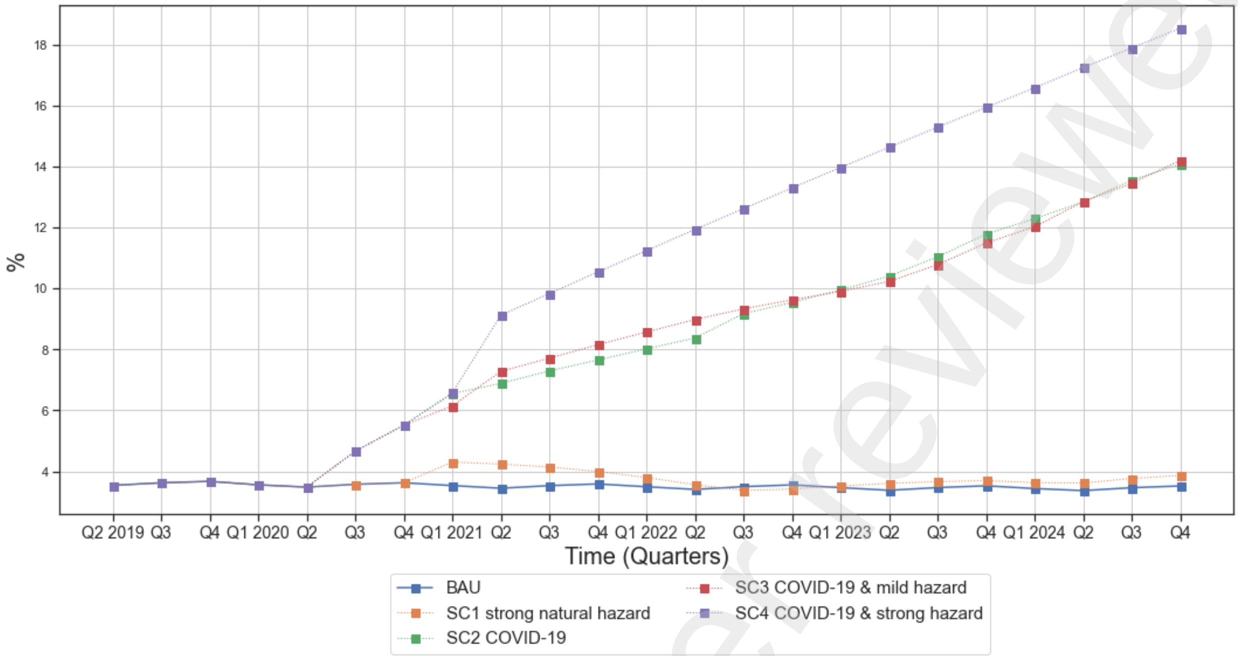
5.3. Simulation results: government's response and credit constraints

Governments all over the world responded to the COVID-19 epidemic with fiscal and monetary policies in an unprecedented manner to mitigate its socio-economic impacts (The World Bank, 2020a). In this section, we analyse the impact of varying government's fiscal efforts on the recovery. Further, we consider scenarios of fiscal and monetary policy complementarity. We assess the effectiveness of public response measures with respect to different conditions in the credit market, i.e. the willingness and ability of banks to grant loans for firms to finance the recovery. Our aim is to investigate the conditions for effective post-crisis fiscal and monetary policies.

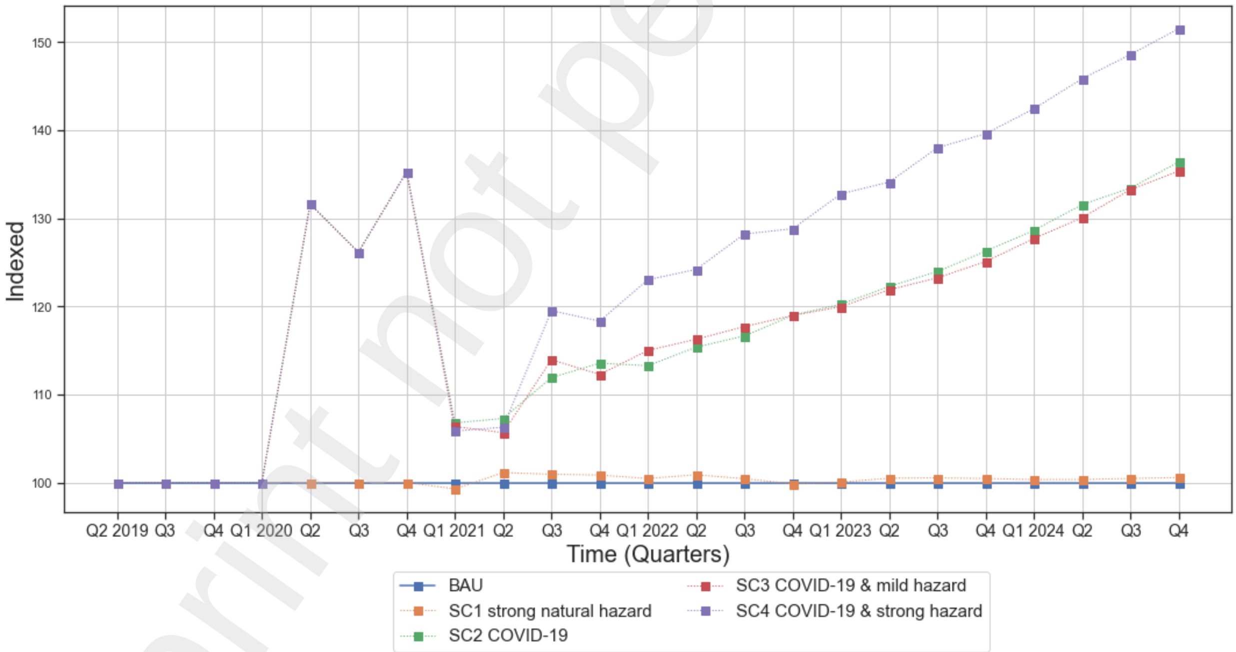
We conduct a sensitivity analysis of government spending during the crisis ΔG as a percentage of Nominal GDP, considering varying levels of constraining factors (such as a minimum Capital Adequacy Ratio $C\bar{A}R$, bank's credit supply, see Eq. 26). We combine 10 levels of government spending with 10 conditions of the credit market for each COVID-19, natural hazard or compound shock scenario. We obtain 100 observations for each scenario that show the effect on real GDP and on public debt to GDP ratio up to 4 years after the shock, as shown in the $3D$ plots (Figure 5.4 - 5.7). Real GDP and debt to GDP ratios are indexed against the BAU scenario. The sensitivity analysis allows to understand the relevance of individual policy responses and their interaction with financial constraints. It also allows to identify non-linearities and drivers of tipping points, which could affect the qualitative and quantitative model results.

Our results yield three important insights with respect to the role of bank lending, government spending effectiveness and complementarity of fiscal and monetary policies.

First, supply-side constraints in the economy, i.e. banks' procyclical lending, add up to the non-linearity of economic impacts (Figures 5.4a and 5.4b). In particular, banks' lending is crucial during the recovery to inject liquidity and prevent firms to go out of business. When banks revise their lending conditions (i.e. the cost of capital) to firms in response to large, compounding shocks, firms' ability to invest in the recovery is impaired, and unemployment increases due to layoffs (SC4). As a consequence, the economy faces a long-lasting negative effect (hysteresis) as unemployment and



(a) Unemployment Rate



(b) Public Debt to GDP Ratio

Figure 5.3: **Unemployment Rate and Public Debt to GDP Ratio** (5 years time span). The x-axis shows the timeline of the simulation lasting until the fourth quarter in 2024 on a quarterly basis. The y-axis shows a) the unemployment rate (upper figure) for Mexico in percentage terms and b) public debt to GDP ratio (lower figure) for Mexico indexed against the BAU scenario considering no COVID-19 or natural hazard shock occurring (BAU = 100).

public debt further increase. Overall, GDP does not catch up and financial stability conditions of the country deteriorates.

Second, the increase in government spending in the aftermath of the shocks provides an important stimulus to domestic demand and thus to GDP (Figure 5.4), creating the conditions for the recovery. Additional fiscal spending does not induce a trade-off for public debt sustainability if banks keep lending (Figure 5.5). However, there is a threshold over which the increase in government spending (i.e., over 10% GDP) starts to be counter-effective for GDP and public debt ratios. At that point, firms are not able to satisfy the additional demand being constrained access to credit. In addition, the worsening of firms' financial conditions in sectors affected by the hurricane (firms with productive capital located in areas exposed to the shock) and by COVID-19 (firms in tourism, export of raw materials and intermediate goods, and services) limits their ability to repay loans, thus weakening banks' balance sheets and financial stability. Banks, in turn, to comply with regulatory requirements (Basel III) tighten firms' access to credit and thus limit their new investments.

Finally, complementary fiscal and monetary policy (i.e. the central bank lowering its policy rate) could increase the impact of government spending. Our results suggest that monetary policy has a positive effect on real GDP via price signaling (Figure 5.6). The resulting GDP growth contributes to keep the public debt to GDP ratio under control and to decrease the constraint of access to liquidity. Nevertheless, the conditions for fiscal and monetary policy complementarity to be effective depend on the size of the natural hazard shock. If the shock is mild (SC3) (Figure 5.6), coordinated fiscal and monetary policy stimulate investments and consumption. They also contribute to improve banks' balance sheet (lower Non-Performing Loans) and their ability to lend to firms. If the natural hazard shock is large (SC4) (Figure 5.7), the effect of policy complementarity on the recovery is weaker. Structural adjustments in the labor and credit markets could be needed to create the conditions for government spending to be effectively when risks compound.

Our results indicate that the magnitude and persistence of the COVID-19 shock on the economy depends on i) the initial size of the shock, ii) on the conditions of the credit market (Figures 5.4 and 5.5), and iii) on (complementary) government response policies (Figures 5.6 and 5.7).

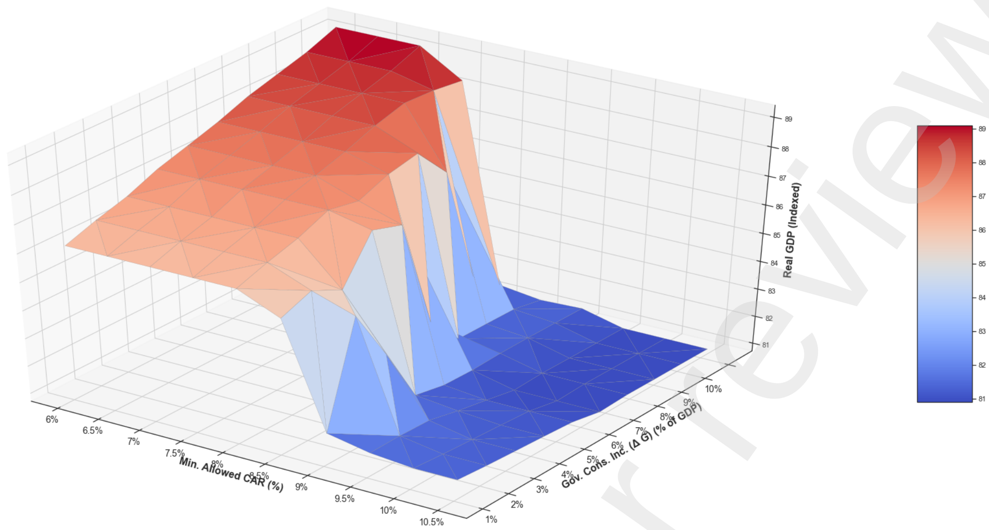
5.4. Compound risk indicator

With a compound risk indicator (CRI) we quantify the indirect impacts of compounding of COVID-19 and natural hazard (in our application, hurricanes) on GDP growth. We consider the potential non-linear dynamics that emerge as the result of endogenous interactions between sectors and agents of the EIRIN economy and finance. When non-linearities emerge, the shock caused by compound risks is more (or less) than the sum of the shocks generated by individual risks considered separately.

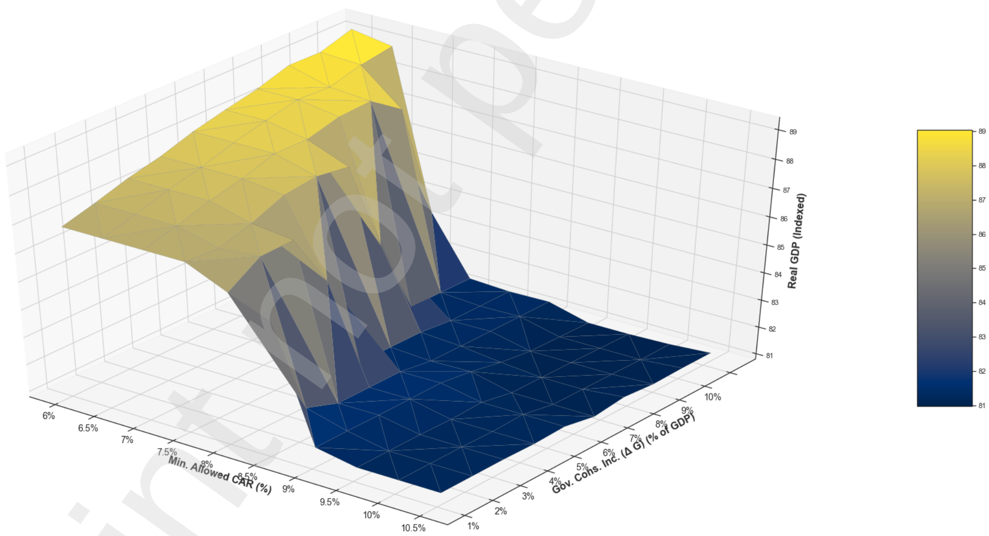
The CRI allows to quantitatively assess the effects of the compound risks with respect to the individual pandemic and climate risks, as follows:

$$CRI_t = \frac{impact_{compound,t}}{impact_{natural\ hazard,t} + impact_{COVID-19,t}} * 100 \tag{34}$$

where the impact is measured in this application in terms of GDP loss, while the scenarios refer to COVID-19 only shock, natural hazard only shock and compound COVID-19 and natural hazard shock.

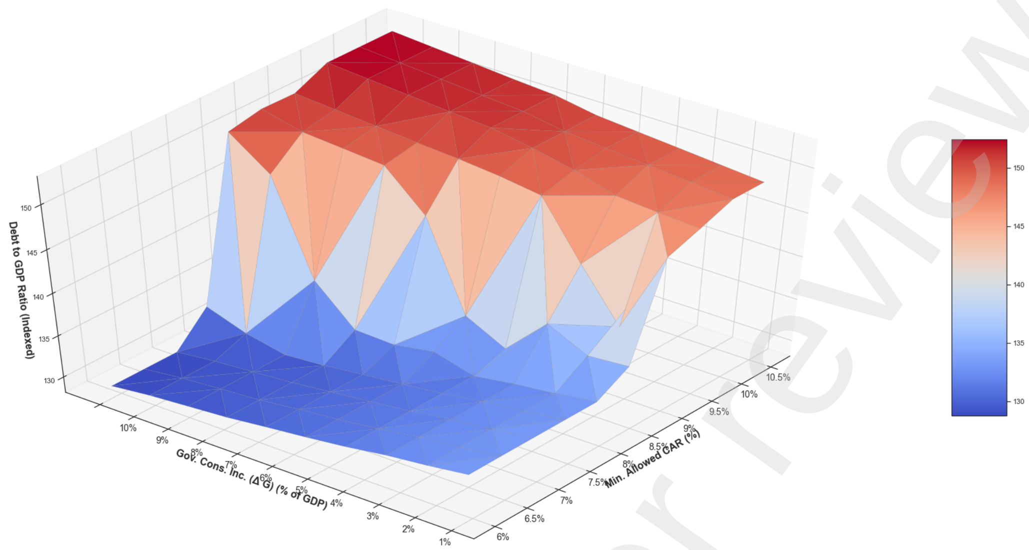


(a) Sensitivity of real GDP - COVID-19 only scenario (SC2)

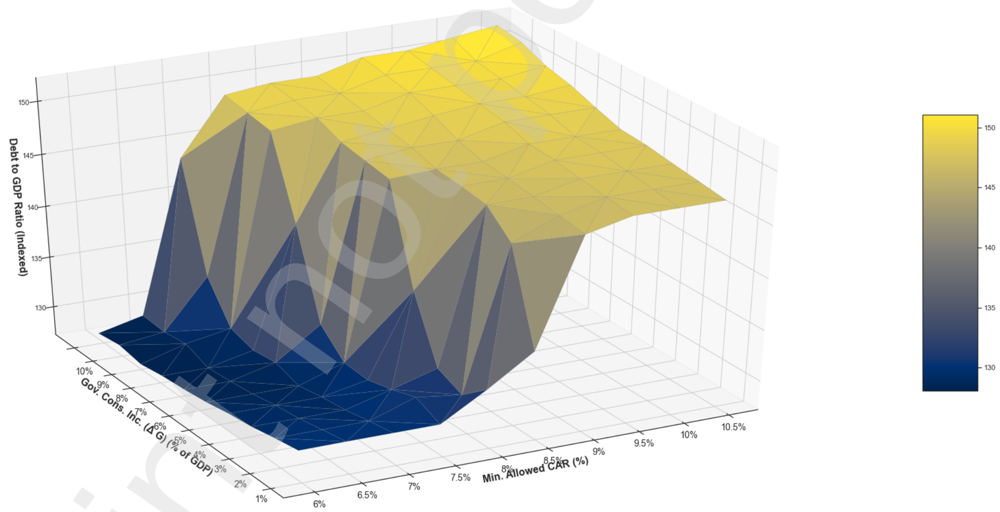


(b) Sensitivity of real GDP - compound COVID-19 and strong hazard scenario (SC4)

Figure 5.4: **Sensitivity of real GDP to an increase in government spending and stronger credit constraints** (represented by a minimum required capital adequacy ratio (CAR)) 5 years after the shock. The red blue surface plot (a) refers to the COVID-19 only scenario (SC2). The blue yellow surface plot (b) refers to the compound COVID-19 and strong hazard scenario (SC4). The y-axis shows the percentage of additional government spending (ΔG) during the COVID-19 shock. The x-axis shows the minimum required Capital Adequacy Ratio (CAR). The z-axis shows the impact on real GDP.

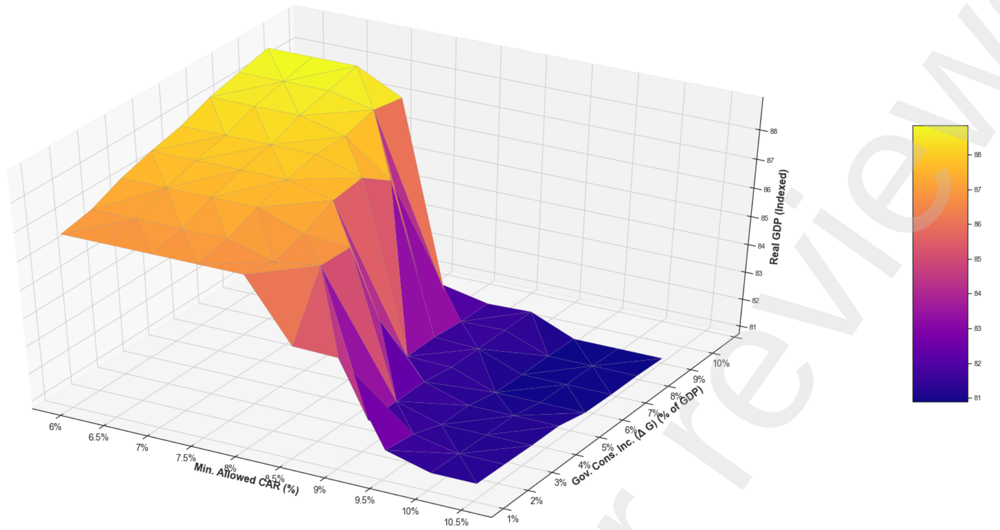


(a) Sensitivity of the debt to GDP ratio - COVID-19 only scenario (SC2)

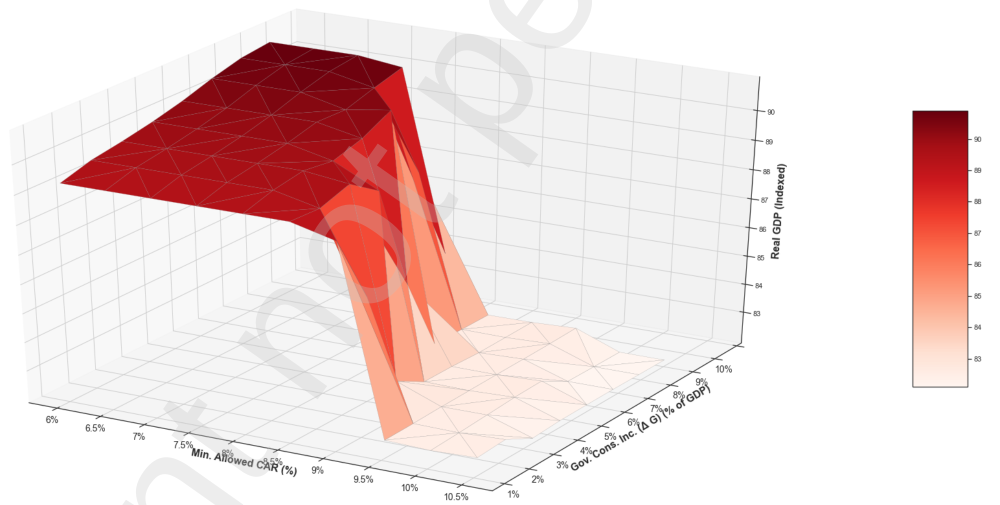


(b) Sensitivity of the debt to GDP ratio - compound COVID-19 and strong hazard scenario (SC4)

Figure 5.5: **Sensitivity the debt to GDP ratio to an increase in government spending and stronger credit constraints** (represented by a minimum required capital adequacy ratio (CAR)) 5 years after the shock. The red blue surface plot (a) refers to the COVID-19 only scenario (SC2). The blue yellow surface plot (b) refers to the compound COVID-19 and strong hazard scenario (SC4). The y-axis shows the percentage of additional government spending (ΔG) during the COVID-19 shock. The x-axis shows the minimum required Capital Adequacy Ratio (CAR). The z-axis shows the impact on the debt to GDP ratio.

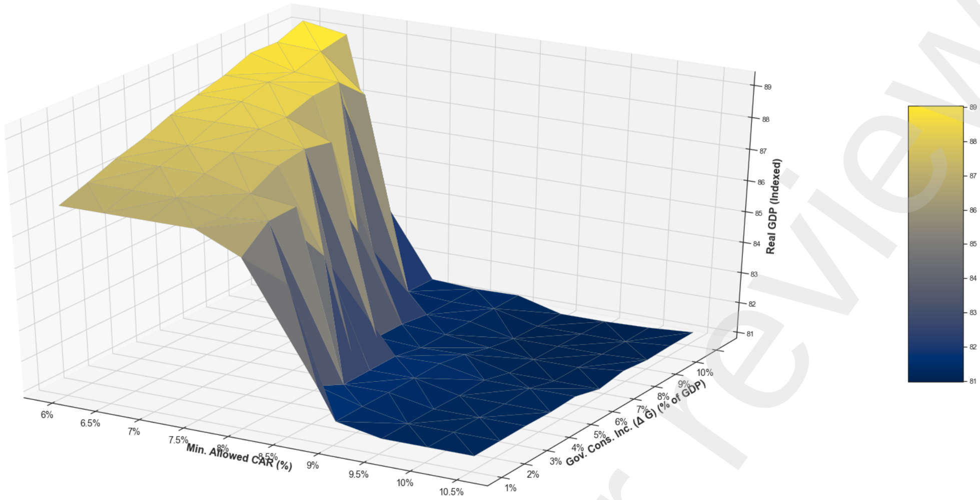


(a) Sensitivity of real GDP - compound COVID-19 and mild hazard scenario (SC3) - fiscal policy only

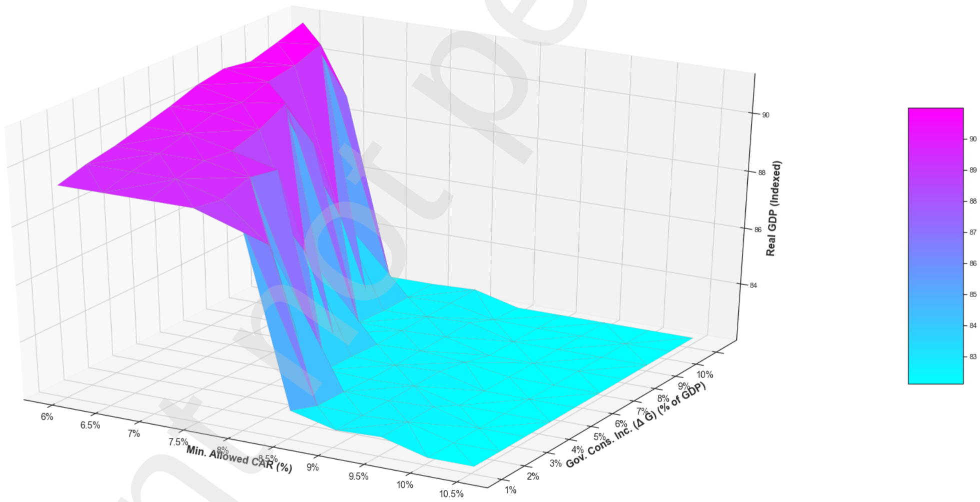


(b) Sensitivity of real GDP - compound COVID-19 and mild hazard scenario (SC3) - complementary fiscal and monetary policy

Figure 5.6: **Sensitivity of real GDP to an increase in government spending, stronger credit constraints (represented by a minimum required capital adequacy ratio (CAR)), with and without complementary monetary policy** 5 years after the shock. The purple-yellow surface plot (a) refers to the COVID-19 and mild hazard scenario (SC3) with only fiscal policy response. The red surface plot (b) refers to the compound COVID-19 and mild hazard scenario (SC3) with complementary monetary policy in place. The y-axis shows the percentage of additional government spending (ΔG) during the COVID-19 shock. The x-axis shows the minimum required Capital Adequacy Ratio (CAR). The z-axis shows the impact on real GDP.



(a) Sensitivity of real GDP - compound COVID-19 and strong hazard scenario (SC4) - fiscal policy only



(b) Sensitivity of real GDP - compound COVID-19 and strong hazard scenario (SC4) - complementary fiscal and monetary policy

Figure 5.7: **Sensitivity of real GDP to an increase in government spending, stronger credit constraints (represented by a minimum required capital adequacy ratio (CAR)), with and without complementary monetary policy** 5 years after the shock. The dark-yellow surface plot (a) refers to the COVID-19 and strong hazard scenario (SC4) with only fiscal policy response. The turquoise-pink plot (b) refers to the compound COVID-19 and strong hazard scenario (SC4) with complementary monetary policy in place. The y-axis shows the percentage of additional government spending (ΔG) during the COVID-19 shock. The x-axis shows the minimum required Capital Adequacy Ratio (CAR). The z-axis shows the impact on real GDP.

The CRI can present the following modes:

- $CRI < 100$: non-linearities emerge but the shock triggered by the compound risk is lower than the sum of the individual shocks caused by the natural hazard and COVID-19 risks.
- $CRI = 100$: there is a linear relation between the shock caused by the compound risk and the individual shocks resulting from natural hazard and COVID-19 risks.
- $CRI > 100$: non-linearities emerge causing the shock triggered by the compound risk to be higher than the sum of the individual shocks caused by natural hazard and COVID-19 risks.

Figure 5.8 shows the compound risk indicator in relation to the simulated scenarios. When COVID-19 compounds with the hurricane (SC3 and SC4), the interaction of demand and supply side shocks leads to non-linear amplification of direct impacts on GDP. Firms revise future demand expectations and consequently cut investments, reducing aggregate supply because no additional capacity is needed to serve demand. Unemployment increases, wages fall due to the Phillips curve dynamics, and the public debt to GDP ratio increases. The degree of non-linearity, however, depends on the size of the hurricane shock (Figure 5.8). A small compound hurricane shock (SC3) improves the COVID-19 situation in the short term (CRI $<$ 100), as a result of the the additional investment stimulus. In the years after the shock (2022), however, impacts non-linearly increase (CRI $>$ 100), as the deteriorated economic conditions from COVID-19 lead to lower production capacity needs than firms anticipated before. This over-investment leads to additional private debt interest payments for slack capital stock. Both effects, the stimulus and the over-investment, are small in scale, however, allowing the non-linearity of compound shock impacts to smooth out after 2023 (CRI = 100). A larger but less frequent hurricane shock (SC4) leads to higher non-linearity due to higher constraints, both from labor and credit side. Firms are impeded for investment by lacking access to credit, leading to a non-linear shock amplification (CRI $>$ 100) in the years to come. This indicates high future vulnerability as climate change is expected to shift the distribution of hurricane occurrence (IPCC, 2018) and increases the probability of losses due to compound events (Zscheischler et al., 2018).

6. Conclusion

In this paper, we have quantitatively assessed the impact of the COVID-19 shock on macroeconomic and credit market performance in Mexico. Then, we analysed the impact of banks' lending behavior on firms' investment decisions, on the effectiveness of government policies, and on sovereign debt sustainability. Finally, we assessed the compounding COVID-19 and climate physical risks, across scenarios of varying magnitude and timing of shocks. We further developed and calibrated the EIRIN Stock-Flow Consistent behavioral model. EIRIN is endowed with heterogeneous agents and sectors characterised by adaptive expectations. Firms' investment decisions are endogenously generated and based on the Net Present Value. Importantly, the model includes endogenous money, banks and financial markets, and the interaction between real and monetary cycles. These characteristics allow us to analyse the risk transmission channels and drivers of reinforcing feedbacks that give rise to non-linear dynamics and amplification effects in the economy, credit market and public finance.

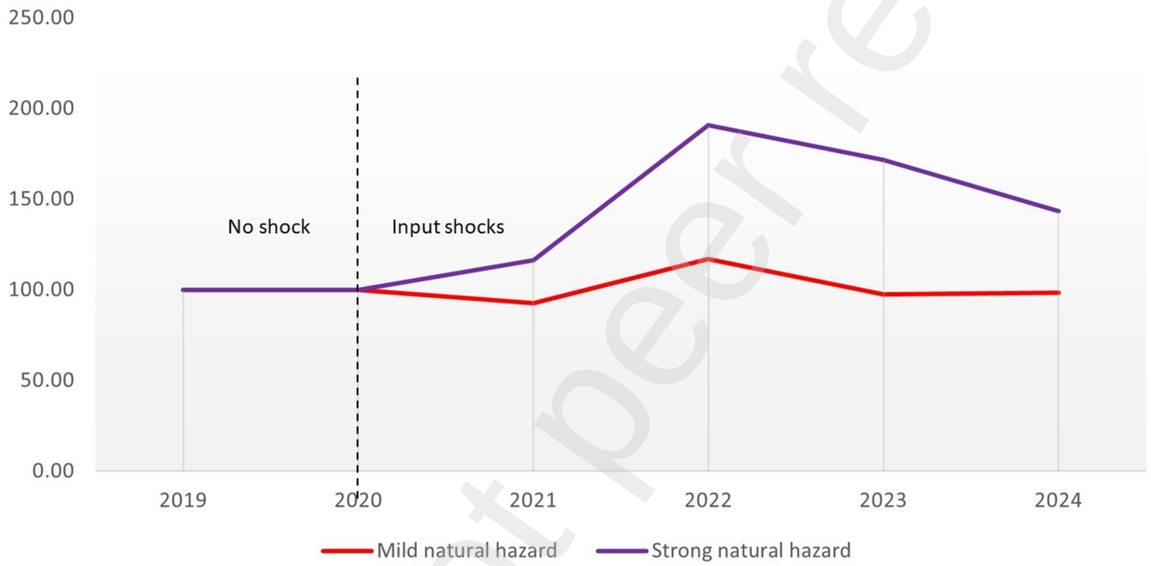


Figure 5.8: **Compound risk indicator** showing the non-linear amplification effects resulting from the compounding of COVID-19 and climate shocks happening in 2020. The x-axis shows the timeline of the simulation until 2024 on an annual basis. The y-axis shows the value of the compound risk indicator indexed against the sum of the singular event scenarios of hurricane only and COVID-19 only, at 100. The vertical dotted line represents the starting point of the input shocks, which occur during 2020. Two compound scenarios are considered: (i) COVID-19 and mild hurricane scenario (red line) and (ii) COVID-19 and strong hurricane scenario (purple line). Being an index, we do not present results in percentage terms.

We have applied the model to the case study of Mexico, due to its socio-economic, climate and COVID-19 vulnerability conditions.

Our results yield the following policy-relevant insights to inform the design of COVID-19 recovery policies aimed to strengthen fiscal and financial resilience:

- The risk transmission channels are shock specific and so are the drivers of reinforcing feedbacks in the economy and finance.
- Credit market constraints in the economy, i.e. banks' ability and willingness to lend, limit firms' ability to invest in the economy.
- When COVID-19 and climate physical risks compound, they trigger non-linear dynamics that amplify the magnitude of the economic shocks and their persistence over several years (hysteresis effect). In particular, when strong hurricanes compound with the COVID-19 shock, they prevent GDP from returning to its pre-COVID GDP path in the short- to midterm.
- Timely increase in government's fiscal spending, coupled with central bank's monetary policy, is crucial to support the economic recovery by replacing falling private demand, affecting banks and firms' expectations about the recovery, and thus their lending and investment decisions.
- However, procyclical bank's lending counteract the effectiveness of fiscal stimulus.
- Post-crisis fiscal policies that support a "business as usual" recovery create the conditions for future socio-economic and financial vulnerabilities (e.g. debt sustainability).

Our analysis highlights the importance of introducing compound risk considerations in governments' fiscal and financial risk management to create the conditions for building resilience. In this regard, the economic analysis of compounding risks requires models that are able to embed the underlying nature of those risks, departing from strong assumptions on the structure of the economy and agents' behaviours. On the one hand, our analysis can be extended to include other financial actors and financial policies (e.g. macroprudential). On the other hand, it could be extended to consider the role of biodiversity loss and natural resource depletion in compound risk amplification.

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Appendix A. EIRIN Balance Sheet, Transaction Flow Matrix and Net Worth Matrix

	H_w	H_k	C_k	C_l	K	EN	BA	CB	G	ROW	$\sum$
Tangible capital			$p_K K_{C_k}$	$p_K K_{C_l}$		$p_K K_{EN}$					$p_K K$
Inventories			$p_{C_k} I_{C_k}$								$p_{C_k} I_{C_k}$
Gold in the vault								M_{CB}			M_{CB}
gov bonds		$p_B n_{H_k}$					$p_B n_{BA}$	$p_B n_{CB}$	$-p_B n_G$		0
Bank's loans			$-L_{C_k}$	$-L_{C_l}$		$-L_{EN}$	L_{BA}				0
CB's loan							$-L_{CB}$	L_{CB}			0
Bank's deposits	M_{H_w}	M_{H_k}	M_{C_k}	M_{C_l}	M_K	M_{EN}	$-D_{BA}$		M_G		0
CB's reserves							M_{BA}	$-M_{fiat}$		M_{ROW}	0
Equity (net worth)	$-E_{H_w}$	$-E_{H_k}$	$-E_{C_k}$	$-E_{C_l}$	$-E_K$	$-E_{EN}$	$-E_{BA}$	$-E_{CB}$	$-E_G$	$-E_{ROW}$	$-E_{EIRIN}$
$\sum$	0	0	0	0	0	0	0	0	0	0	0

Table A.5: Balance sheet matrix of the EIRIN economy. Each column represents the balance sheet of an agent or sector. Assets are reported with no sign while liabilities with a negative sign. Each column always sums to zero to highlight the definition of equity (or net worth). Except for real assets, the table rows also sum to zero to highlight the financial interlinkages among sectors, i.e. that what is a financial asset for a sector is a liability for another sector. In the matrix each subscript represents the index of the agent to which the stock refers.

Cash flows from:	H_w	H_k	C_k	C_l	K	EN	BA	CB	G	ROW	Σ
Consumption of:											0
- goods	$-C_{H_w}$	$-C_{H_k}$	$p_{C_k}q_{C_k}$	$p_{C_l}q_{C_l}$					$-C_G$		0
- energy	$-p_{EN}q_{EN}^{H_w}$	$-p_{EN}q_{EN}^{H_k}$	$-p_{EN}q_{EN}^{C_k}$	$-p_{EN}q_{EN}^{C_l}$	$-p_{EN}q_{EN}^{K}$	$p_{EN}q_{EN}$					0
Imports	$-q_{H_w}p_{R_c}$	$-q_{H_k}p_{R_c}$	$-p_Rq_R$							$p_Rq_R + q_Hp_{R_c}$	0
Exports			$p_{C_k}q_{C_k}$	$p_{C_l}q_{C_l}$		$p_{EN}q_{EN}$				$-p_{C_k}q_{C_k}$ $-p_{C_l}q_{C_l}$ $-p_{EN}q_{EN}$	0
Tourism				TU_{C_l}						$-TU_{ROW}$	0
Remittances	R_{H_w}	R_{H_k}								$-R_{ROW}$	0
Wages	Y_{H_w}		$-N_{C_k}w_{high}$	$-N_{C_l}w_{low}$	$-N_Kw_{high}$				$-N_Gw_{high}$		0
Interests:											
- bonds' coupons		c_Bn_{Hk}					c_Bn_{BA}	c_Bn_{CB}	$-c_Bn_G$		0
- bank's loans			$-r_DL_{C_k}$	$-r_DL_{C_l}$		$-r_DL_{EN}$	Y_{BA}				0
- CB's loan							$-r_{CB}L_{CB}$	$r_{CB}L_{CB}$			0
Income tax	$-T_{H_w}$	$-T_{H_k}$	$-T_{C_k}$	$-T_{C_l}$	$-T_K$	$-T_{EN}$			T_G		0
Dividend payout		$Y_{H_k}^d$	$-d_{Ck}$	$-d_{Cl}$	$-d_K$	$-d_{EN}$	$-d_{BA}$				0
Seignorage								S_{CB}	S_G		0
	=	=	=	=	=	=	=	=	=	=	
(Net Cash flow)	$+NCF_{H_w}$	$+NCF_{H_k}$	$+NCF_{C_k}$	$+NCF_{C_l}$	$+NCF_K$	$+NCF_{EN}$	$+NCF_{BA}$	$+NCF_{CB}$	$+NCF_G$	$+NCF_{ROW}$	0
	+	+	+	+	+	+	+	+	+	+	
Investment in:											
- capital			$-p_Kq_K^{C_k}$	$-p_Kq_K^{C_l}$	p_Kq_K						0
Δ Loans			ΔL_{C_k}	ΔL_{C_l}		ΔL_{EN}	$-\Delta L_{BA} + \Delta L_{CB}$	$-\Delta L_{CB}$			0
brown bond issues		$-p_B\Delta n_{H_k}$					$-p_B\Delta n_{BA}$	$-p_B\Delta n_{CB}$	$p_B\Delta n_G$		0
Δ bank's deposits	$-\Delta M_{H_w}$	$-\Delta M_{H_k}$	$-\Delta M_{C_k}$	$-\Delta M_{C_l}$	$-\Delta M_K$	$-\Delta M_{EN}$	ΔD_{BA}		$-\Delta M_G$		0
Δ CB's reserves							$-\Delta M_{BA}$	ΔM_{fiat}		$-\Delta M_{ROW}$	0
$\sum$	0	0	0	0	0	0	0	0	0	0	

Table A.6: Cash flow matrix of agents and sectors in the EIRIN economy. The matrix is divided into two sections. The first section refers to cash receipts or outlays of operating activities with an impact on net worth. The second section refers to cash flows generated by variations in real, financial and monetary assets or liabilities.

	H_w	H_k	C_k	C_l	K	EN	BA	CB	G	ROW
(Net cash flows Table A.6)	$+NCF_{H_w}$	$+NCF_{H_k}$	$+NCF_{C_k}$	$+NCF_{C_l}$	$+NCF_K$	$+NCF_{EN}$	$+NCF_{BA}$	$+NCF_{CB}$	$+NCF_G$	$+NCF_{ROW}$
Capital depreciation			$-\delta_k K_{C_k}$	$-\delta_k K_{C_l}$		$-\delta_K K_{EN}$				
Capital destruction (potentially)			$-\xi_k K_{C_k}$	$-\xi_k K_{C_l}$		$-\xi_K K_{EN}$				
Change of inventories			$p_C \Delta I_C$							
Price change of:										
- tangible capital			$\Delta p_K K_{C_k}$	$\Delta p_K K_{C_l}$		$\Delta p_K K_{EN}$				
- inventories			$\Delta p_C I_C$							
- bonds		$\Delta p_B n_{H_k}$					$\Delta p_B n_{BA}$	$\Delta p_B n_{CB}$	$-\Delta p_B n_G$	
	$-\Delta E_{H_w}$	$-\Delta E_{H_k}$	$-\Delta E_C$		$-\Delta E_K$	$-\Delta E_{EN}$	$-\Delta E_{BA}$	$-\Delta E_{CB}$	$-\Delta E_G$	$-\Delta E_{ROW}$
$\sum$	0	0	0	0	0	0	0	0	0	0

Table A.7: Net Worth Change Matrix. The matrix shows how sectors' net worth changes due to both net cash flows and the price changes of financial assets.

Appendix B. Accounting equations

Appendix B.1. Heterogeneous households

Worker (H_w) (receiving wage income)

Changes in assets:

$$\Delta\ M_{H_w} = Y_{H_w}^{net} - p_{F_L}\ C_{H_w}^{F_L} - p_{F_K}\ C_{H_w}^{F_K} - IM_{H_w} \tag{B.1}$$

where IM_{H_w} is worker household consumption good imports. $Y_{H_w}^{net}$ is the net disposable labor income, net of energy expenses $p_{EN}\ q_{Hw}^{EN}$ and income tax payments,
i.e., $Y_{H_w}^{net} = (1-\tau)\,(N_{high}\ w_{high}\ +\ N_{low}\ w_{low}\ ) - p_E N\ q_{H_w}^{EN} + R_{H_w}$, where R_{H_w} are remittances, τ is the tax rate and N_{high} is the share of the labor force employed in the capital intensive consumption goods sector, in public sector and in capital goods producer sector, while N_{low} represent the share of labor force employed in labor intensive sector,
i.e. $N_{high} = N_{Gov}\ +\ N_{C_k}\ +\ N_K$ and $N_{low} = N_{C_l}$.

Changes in liabilities:

$$\Delta E_{H_w} = \Delta M_{H_w} \tag{B.2}$$

where changes in workers' equity ΔE_{H_w} are all reflected in workers' changes in deposits being the only way workers accumulate wealth.

Capitalist (H_k) (receiving dividend and bonds income)

Changes in assets:

$$\Delta M_{H_K} = Y_{H_k}^{net} - p_{F_L}\ C_{H_k}^{F_L} - p_{F_K}\ C_{H_k}^{F_K}\ -\ \Delta n_{H_k}\ p_B - IM_{H_k} \tag{B.3}$$

where IM_{H_k} is capitalist household consumption good imports. $Y_{H_k}^{net}$ is the net disposable income, net of energy expenses $p_{EN}\ q_{H_k}^{EN}$ and capital income tax payments,
i.e. $Y_{H_k}^{net} = (1-\tau)\left(d_{F_L}\ +\ d_{F_K}\ +\ d_K\ +\ d_{EN}\ +\ +\ d_{BA}\ +\ n_{H_k}^{B}\ c_B\right) - p_{EN}\,q_{H_k}^{EN} + R_{H_k}$ where R_{H_k} are remittances, τ is the tax rate applied to the dividends payout and bonds coupons.
Changes in liabilities:

$$\Delta E_{H_k} = \Delta M_{H_k}\ +\ \Delta n_{H_k}\ p_B +\ n_{H_k}\ \Delta p_B \tag{B.4}$$

where $\Delta n_{H_k}\ p_B$, i.e. the change in value of the bond portfolio held by the capitalist household. The change depends both on the purchase of new bonds Δn_{H_k} issued by the government and the change in bond price $\Delta\ p_B$.

Appendix B.2. Consumption goods producers (F_L + F_K)

Changes in assets:

$$\Delta M_j = \Pi_j - d_j - p_K\, I_j + \Delta L_j \tag{B.5}$$

where I_j represent the investment, Π_j is the net operating profit, i.e. $\Pi_j = p_j \left(C^j_{H_w} + C^j_{H_k}\right) + TU_{F_L} + G_j + p_{C_m} q^X_{C_m} - w_x\ N_j - p_R\, q_R - p_{EN}\, q^{EN}_j - r^j_D\ L_j - T_j$, with $j = F_L, F_K$ and $x = high, low$. T_j is the corporate tax, G_j is the government spending expenditures, $p_{C_m} q^X_{C_m}$ are consumption good and intermediate exports, L_j are new loans and d_j is the total dividends payout which is set equal to the net operating profits realized at the previous time step, if positive:

$$\Delta K_j = -\,\delta_j\, K_j\ -\ \xi_j\, K_j + I_j \tag{B.6}$$

$$\Delta\, I_{F_K} = q_{F_K} - C^{F_K}_{H_w} - C^{F_K}_{H_k} \tag{B.7}$$

Changes in equity:

$$\Delta E_j = \Delta M_j + \Delta \left(p^j_C\, IN_j\right) + \Delta(p_k\, K_j) - \Delta L_j \tag{B.8}$$

Changes in consumption good firm's equity consist of deposit changes ΔM_j, changes in its inventory valuation where $\Delta \left(p^j_C\, IN_j\right) = \Delta p^j_C\, IN_j + p^j_C\, \Delta IN_j$ and changes in employed capital $\Delta(p_k\, K_j) = \Delta p_k\, K_j + p_k\, \Delta K_j$ as well as changes in liabilities ΔL_j.

Appendix B.3. Capital goods firm (K)

Changes in assets:

$$\Delta M_K = \Pi_K - d_K \tag{B.9}$$

where Π_K is the net operating profit, i.e. $\Pi_K = p_K\, I_K - w_{high}\, N_K - p_{EN}\, q^{EN}_K - T_K$, and we have $I_K = I_j + I_E$. d_K is the total dividend payout set equal to the net operating profit, if positive, realized at the previous time-step.

Changes in liabilities:

$$\Delta E_K = \Delta M_K \tag{B.10}$$

(A.10)

Appendix B.4. Energy Firm (EN)

Changes in assets:

$$\Delta M_{EN} = \Pi_{EN} - d_{EN} - p_K\, I_{EN} + \Delta\, L_{EN} \tag{B.11}$$

where Π_{EN} is the net operating profit, i.e $\Pi_{EN} = p_{EN} \sum q_n^{EN} - p_O\, q_O - r_D^j L_{EN} - T_{EN}$, and d_{EN} is the total dividend payout set equal to the net operating profit, if positive, realized at the previous time step.

$$\Delta\, K_{EN} = -\delta_{EN}\, K_{EN} - \xi_{EN}\, K_{EN} + I_{EN} \tag{B.12}$$

Changes in equities:

$$\Delta\, E_{EN} = \Delta\, M_{EN} + \Delta\, p_K\, K_{EN} + p_K\, \Delta\, K_{EN} - \Delta\, L_{EN} \tag{B.13}$$

Appendix B.5. Commercial bank (BA)

Changes in assets:

$$\Delta\, M_{BA} = \Pi_{BA} + \sum_n \Delta\, D_n + \Delta\, n_{BA}\, p_B - \sum_n \Delta\, L_n \tag{B.14}$$

where Π_{BA} is the operating profit, i.e. $\Pi_{BA} = r_D^n\ (\sum_n L_n) - r_{CB}\, L_{CB} + n_{BA} c_B$, D_n are deposits and d_{BA} is the total dividend payout set equal to the operating profit, if positive, realized at the previous time step, and if the bank fulfils a capital requirement rule, i.e. its equity capital is higher than a given percentage of total outstanding loans.

Changes in liabilities:

$$\Delta\, D_{BA} = \Delta\, M_{H_w} + \Delta\, M_{H_k} + \Delta\, M_{F_K} + \Delta\, M_{F_L} + \Delta\, M_{EN} + \Delta\, M_K + \Delta\, M_{Gov} \tag{B.15}$$

$$\Delta\, E_{BA} = \Delta M_{BA} + \sum_n \Delta\, L_n + \Delta\, n_{BA}\, p_B + n_{BA}\, \Delta\, p_B - \sum_n \Delta\, D_n - \Delta\, L_{CB} \tag{B.16}$$

Appendix B.6. Government (G)

Changes in assets:

$$\Delta M_G = T_{H_w} + T_{H_k} + T_{F_K} + T_{F_L} + T_K + T_{EN} + S_G - n\, c_B - G_j + \Delta n_G\, p_B + n_G \Delta p_B + \Delta\, L_{ROW} \tag{B.17}$$

where S_G represent seignorage, L_{ROW} are loans provided by international institutions to support government spending. The different tax proceedings are computed as a $\tau\%$ of the labor income, capital income and operating profits realized at the previous time step. For the sake of simplicity, we assume that the operating profits of the bank are not subject to taxation.

Changes in liabilities:

$$\Delta\, E_G = \Delta M_G - \Delta n_G\, p_B + n_G \Delta p_B \tag{B.18}$$

Appendix B.7. Central Bank (CB)

Changes in assets:

$$\Delta\, M_{CB} = r_{CB}\, L_{CB} - S_G - \Delta\, L_{CB} \tag{B.19}$$

where Seignorage S_G is set equal to the value of $r_{CB}\, L_{CB}$ at the previous time step.

Changes in liabilities:

$$\Delta\, D_{CB} = \Delta\, M_{BA} \tag{B.20}$$

$$\Delta\, FB_{CB} = \Delta\, M_{ROW} \tag{B.21}$$

$$\Delta\, E_{CB} = \Delta\, M_{CB} + \Delta\, L_{CB} - \Delta\, D_{CB} - \Delta\, FL_{CB} \tag{B.22}$$

where FB_{CB} represent foreign liabilities.

Appendix B.8. Foreign Sector (ROW)

Changes in assets:

$$\Delta M_{ROW} = p_R\, q_R + IM_{H_w} + IM_{H_k} - R_{H_w} - R_{H_k} - EX_{F_L} - EX_{F_K} - TU_{F_L} - \Delta\, L_{ROW} \tag{B.23}$$

Changes in liabilities:

$$\Delta\, E_{ROW} = \Delta\, M_{ROW} \tag{B.24}$$

Appendix C. Behavioral equations

Appendix C.1. Heterogeneous households (H_w and H_k)

$$Y_{H_w} = \sum (N_{high} w_{high} + N_{low} w_{low}) \tag{C.1}$$
$$Y_{Hk} = n_{H_k}\, c_B + \sum d_i \tag{C.2}$$
$$Y_m^{net} = (1-\tau)\, Y_m - p_{EN}\, q_m^{EN} + R_m \tag{C.3}$$
$$C_m = Y_m^{net} + \rho \left(M_m - \phi\, Y_m^{net} \right) \tag{C.4}$$
$$C_m^{F_L} = \beta\, C_m \tag{C.5}$$
$$C_m^{F_K} = (1-\beta)\, C_m \tag{C.6}$$

with $m = H_w, H_k$.

Appendix C.2. Labor market

$$w_{high} = ((1-z)\, w_{max} + z\, w_{min} + w_{max})/2 \tag{C.7}$$
$$w_{low} = ((1-z)\, w_{max} + z\, w_{min} + w_{min})/2 \tag{C.8}$$
$$\Delta w = (-\theta_1 + \theta_2\, e) w \tag{C.9}$$
$$N_{high}\, w_{high} + N_{low}\, w_{low} = (N_{high} + N_{low})\, w \tag{C.10}$$
$$\widehat{N_j} = \min \left(\widehat{q_j^C}, \gamma_j^K K_j \right) / \gamma_j^N \tag{C.11}$$
$$\widehat{N_K} = \min \left(\sum_n \widehat{I}_n / \gamma_K^N,\ (1+\chi)\, N_{K,t-1} \right) \tag{C.12}$$

Appendix C.3. Consumption good producers (F_L and F_K)

$$q_j^C = min\, (\gamma_j^N\, N_j,\ \gamma_j^K\, K_j,\ \gamma_j^E\, q_j^{EN},\ \gamma_j^R\, q_j^R) \tag{C.13}$$

with $j = F_L, F_K$.

$$p_j^C = \frac{w_j\, N_j + r_D^j\, L_j + p_{EN}\, q_j^{EN} + p_R\, q_j^R}{q_j} \tag{C.14}$$

$$\widetilde{q_{F_K}} = \min \left(IN_{F_K} + q_{F_K},\ \frac{C_{H_w}^{F_K} + C_{H_k}^{F_K}}{p_{F_K}^C} \right) \tag{C.15}$$

$$\widetilde{q_{F_L}} = \min \left(q_{F_L},\ \frac{C_{H_w}^{F_L} + C_{H_k}^{F_L} + Tu_{F_L}}{p_{F_L}^C} \right) \tag{C.16}$$

Appendix C.4. Energy Firm (EN)

$$q_{EN} = q_{H_w}^{EN} + q_{H_k}^{EN} + q_{F_L}^{EN} + q_{F_K}^{EN} + q_{K}^{EN} \tag{C.17}$$

$$p_{EN} = (1+\mu_{EN}) \left(\frac{r_D^{EN}\, L_{EN} + p_O\, q_O}{q_{EN}} \right) \tag{C.18}$$

Investment decision

$$\hat{I_n} \;=\; \max\left(\bar{K_n} - (1-\ \delta\, K_n) - (1-\ \xi\, K_n)\,, 0\right) \tag{C.19}$$

$$I_n \;\leq\; M_n + \Delta L_n \tag{C.20}$$

$$NPV_j \;=\; -p_K\, I_j + \sum_{t=1}^{+\infty} \left(\frac{\Delta\, \widehat{q_j^C}\, p_j - w_j\, \Delta\, N_j - \Delta q_j^R\, p_R - \Delta\, q_j^E\, p_{EN}}{1 + r_D^j} \right) \tag{C.21}$$

Appendix C.5. Capital good firm (K)

$$q_K \;=\; I_{F_L} + I_{F_K} + I_{EN} \tag{C.22}$$

$$p_K \;=\; (1+\mu_K) \left(\frac{w_{high}\, N_K + q_K^{EN}\, p_{EN}}{q_K} \right) \tag{C.23}$$

Appendix C.6. Commercial bank (BA)

$$r_D^{n,T} \;=\; r_{D,t-1}^n \left(1 + \left(\frac{\frac{L_n}{E_n} - \psi}{\psi} \right) \right) \tag{C.24}$$

$$r_{D,t}^n \;=\; r_{D,t-1}^n + \lambda_r\, (r_D^{n,T} - r_{D,t-1}^n) \tag{C.25}$$

$$\Delta\, L_n \;\leq\; max\left(\frac{E_{BA}}{CAR} - L_{n,t-1}, 0 \right) \tag{C.26}$$

Appendix C.7. Government (G)

$$\Delta\, n_G = \frac{\bar{M} - M_G}{p_B} \tag{C.27}$$

Appendix C.8. Central bank (CB)

$$r_{CB} = \omega_\pi(\pi - \bar{\pi}) + \omega_u(u - \bar{u}) \tag{C.28}$$

$$\pi = \frac{q^C_{F_L}}{q^C_{F_K} + q^C_{F_L}} \frac{\Delta\, p_{F_L}}{p_{F_L}} + \frac{q^C_{F_K}}{q^C_{F_K} + q^C_{F_L}} \frac{\Delta\, p_{F_K}}{p_{F_K}} \tag{C.29}$$

$$u = 1 - \frac{N_K + N_{F_L} + N_{F_K}}{N_{tot}} \tag{C.30}$$

$$e = \frac{N_K + N_{F_L} + N_{F_K}}{N_{tot}} \tag{C.31}$$