Leaning against persistent financial cycles with occasional crises*

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Abstract

We study conditions under which a leaning against the wind (LAW)-type monetary policy is advisable to address risks to financial stability. We do so within a regime-switching dynamic stochastic general equilibrium (DSGE) model with endogenous crises and persistent financial cycles based on partly backward-looking house price beliefs. Under empirically plausible financial cycles, LAW increases inflation volatility because it amplifies the effects of supply shocks on inflation. It also leads to a lower average inflation, resulting in more frequent episodes of a binding lower bound on interest rates. LAW is advisable only if (i) the central bank puts more weight on output stability or (ii) financial cycles are less persistent than observed. Higher long-run capital requirements are better suited to address risks to financial stability as they reduce the fluctuations in inflation and output considerably by reducing both the frequency of effective lower bound episodes and the severity of crises.

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Introduction

Should central banks take financial imbalances into account in monetary policy decisions and raise interest rates above levels implied by their mandates, despite the likely ensuing economic costs?[1] For more than two decades, academic and central banking communities have grappled with the question of whether the so-called leaning against the wind (LAW)-type monetary policy is overall beneficial, to try and explore how to best protect the economy against the next crash. Those supporting LAW-type monetary policies emphasise the increased financial vulnerabilities following the loose monetary policy stance in most major economies in response to the Global Financial Crisis (GFC) and the Covid-19 pandemic, thereby sowing the seeds of the next financial crisis. In light of these discussions, for instance, the Reserve Bank of New Zealand has been tasked to explicitly consider house prices in its monetary policy decisions since 2022.[2]

Taking stock of these timely considerations, this paper revisits LAW-type monetary policy by departing from the existing literature in multiple ways. First, we explicitly consider the role of persistent financial cycles in our analysis of LAW policies. A major criticism of the LAW-framework in Svensson (2017a), who shows that the costs of implementing LAW-type monetary policy are far larger than the benefits, is in that it does not take into account the persistence of the financial cycle (BIS, 2016). We address this issue by incorporating partly backward-looking (henceforth hybrid) house price expectations. In particular, this type of non-rational house price beliefs prolongs the fluctuations in house prices and household debt as in the actual data (Gelain et al., 2013).[3]

Accounting for the persistence of financial cycles proves crucial in discussions on whether LAW-

[1] We would like to clarify some definitions early on given the motivation of the paper. Within our modelling framework, we proxy "financial imbalances" by either real house price gaps (deviations of real house prices from its long-run trend) or by real household credit gap (deviations of real household credit from its long-run trend). These two financial indicators are shown to be the most robust indicators of financial crashes in major advanced economies over time (see Schularick and Taylor (2012)). We define the current mandates of a modern central bank as price stability and output stability, which is achieved by optimal discretionary monetary policy in normal times within our model. Finally, the benefit of keeping policy rate higher under leaning-against-the-wind (LAW)-type monetary policy is that the central bank could avoid incurring the expected cost of a financial crash, which is given by the output losses multiplied by the probability of a crisis.

[2] See `https://www.rbnz.govt.nz/monetary-policy/about-monetary-policy/monetary-policy-framework` for more details.

[3] Our model matches the empirical persistence found in house prices and household credit more closely than models without hybrid house price expectations. The average duration of a financial cycle in our framework is 25 years, of which 2 years are crisis episodes. This average duration is comparable to that in the empirical analysis by Drehmann et al. (2012). Moreover, our model does not feature limit cycles (see Beaudry et al. (2020)), instead, exogenous shocks drive persistent endogenous processes in our setup.

type monetary policy is beneficial or not and differentiates our work from the existing literature. For instance, Boissay et al. (2021) find LAW-type monetary policy rules to be optimal in a model with rational house price expectations. In contrast, we conclude that systematic LAW[4] is not favourable, mainly due to the higher inflation volatility it induces under prolonged financial cycles, stemming from the amplification of supply shocks under monetary policy reacting to house prices. Adam and Woodford (2021) study the same question in a model with non-rational house price expectations (but without explicit modelling of financial crises as we do), using the notion of near-rational expectations by Woodford (2010), which is a different form of expectation formation process than we employ in our model. A key shortcoming of this type of non-rational house price expectations is that they do not necessarily lead to the empirically-relevant persistence in house prices and household debt, which proves crucial for whether LAW is optimal. We further differ from Adam and Woodford (2021) by capturing an important trade-off between responding to inflation and house prices because house prices do not react to supply-side shocks in these authors' framework. We show that capturing this trade-off is key in the light of supply-side shocks, because LAW tends to increase inflation volatility by amplifying supply shocks if monetary policy responds to house prices. Our framework also nests standard rational house price expectations, which deliver lower persistence in house prices and household debt. We use this nested framework to assess the importance of house price expectations and the role of persistence for the desirability of LAW policies.

We employ an estimated medium-scale New Keynesian (NK) DSGE model of a small open economy (Kravik and Mimir (2019)) to evaluate systematic LAW policies. The model features a housing sector as in Iacoviello (2005) and a banking sector as in Gerali et al. (2010). In addition to including real and nominal rigidities such as external habit formation, investment adjustment costs, variable capacity utilization, price and wage adjustment costs as in Smets and Wouters (2007), it incorporates credit constraints on households and entrepreneurs in the form of loan-to-value restrictions, thereby providing a role for the collateral channel.[5] The model has been extensively used for the analyses of monetary and macroprudential policies. The current paper takes Norwegian Economy Model (NEMO) as the baseline model and integrates it into an endogenous Markov-regime-switching (RS) framework to investigate systematic policy. In

[4]For nonsystematic LAW along the lines of Svensson (2017a) and Kockerols and Kok (2021) see the online appendix section C.

[5]Readers may refer to Appendix D for a detailed model overview and Kravik and Mimir (2019) for a comprehensive documentation.

this paper, we mainly focus on explaining this extension and delegate the descriptions of the underlying model to the appendix.

We investigate systematic LAW-type monetary policy in an endogenous Markov-RS version of NEMO. Our model is fairly rich to cover many key contingencies as it includes seven more regimes.[6] The regimes mainly cover the dimensions of an occasionally binding effective lower bound (ELB), an empirically disciplined endogenous financial crisis, and asymmetric LAW policy. These novel contingencies allow us to address more detailed aspects of the question at hand in a more realistic setting. We then search for the optimal systematic LAW policy, i.e. the response coefficient to a positive real house price gap in the model with the possibility of crises, taking as given the optimal simple rule (OSR) that mimics optimal monetary policy in the model without crises.[7]

We find that systematic LAW is not optimal under prolonged financial cycles. In particular, we find that neither leaning with nor leaning against the wind reduces the central bank's loss so that ignoring house prices is optimal. This is because although systematic LAW reduces both the probability and the severity of crisis episodes, it increases the volatility of inflation substantially in normal times since it amplifies the effects of supply shocks over the business cycle. This feature specifically hinges on the strong countercyclical effect of systematic LAW on housing collateral, restraining domestic demand and leading to larger declines in inflation. In addition, systematic LAW leads to more frequent episodes of a binding ELB given lower average inflation it generates.

We find, however, that the persistence of the financial cycle plays a central role in these findings. Specifically, under rational house price expectations, systematic LAW becomes optimal due to the lower volatility of inflation it brings, thanks to its dampened countercyclical impact on housing collateral and domestic demand. This finding holds despite the lower ergodic means of both inflation and output, since the mean effects of systematic LAW become weaker under less persistent financial cycles. Thus, the central bank loss is lower under a positive degree of systematic LAW.

[6] We solve the Markov RS DSGE model using the Rationality In Switching Environments (RISE) toolbox developed by Junior Maih. RISE is an object-oriented Matlab toolbox for solving and estimating nonlinear RS DSGE models. The toolbox is freely available for downloading at https://github.com/jmaih/RISE_toolbox .

[7] By confining interest to a moderate change from the existing monetary policy rule, our methodology follows Gelain et al. (2013) and Gourio et al. (2017) . We do not consider it to be realistic for the policymakers to significantly change their current reaction to inflation and output under a shift to a financial variable-augmenting policy rule.

Our findings also indicate that a tradeoff between responding more to output and responding to house prices arises under systematic LAW. As house prices are procyclical over the business cycle, a policy rule that responds to output essentially responds to house prices. Our findings confirm this conjecture and document this tradeoff.

Our framework allows us to isolate the effect of the possibility of a crisis, and we find that systematic LAW is not optimal under persistent financial cycles even when a crisis never occurs. This means that the benefits of lower crisis probability and severity due to LAW are more than offset by the detrimental effect of LAW on agents' behaviour in normal times in terms of higher inflation volatility and lower mean inflation. The dynamics of inflation and output in normal times prove to be crucial for the main results because the model economy spends 72% of its time in a no-crisis, no-ELB regime. This result stands in contrast to Gambacorta and Signoretti (2014), which find that LAW is optimal because it reduces both output and inflation volatility due to credit supply considerations. We suspect that their finding results from the absence of persistent financial cycles, which lead to higher inflation volatility under systematic LAW.

We also study optimal LAW-type macroprudential policy in the form of optimal long-run bank capital regulation that minimises the central bank loss.[8] Since we aim to evaluate the effects of macroprudential policy in isolation, we use the baseline monetary policy rule that does not respond to real house prices. While assessing optimal macroprudential policy, we also use the standard central bank loss function that reflects the same preferences of inflation and output stabilisation as in the case of monetary policy. We do not consider an additional financial stability mandate since we would like to conduct a comparable policy experiment to the one related to LAW-type monetary policy.

We find that higher long-run capital requirements reduce both inflation and output volatility. When the long-run capital requirements are higher, the average depth of crises is smaller and the recovery is faster. Although they reduce average output in normal times, they limit the frequency of ELB episodes by raising mean inflation rate. Under higher capital requirements, the banking sector is more resilient to macroeconomic and financial shocks. Therefore, the negative shocks of the same magnitude do not lead to deflationary effects, and the economy performs better.

[8] We also investigate the optimal time-varying Countercyclical Capital Buffer (CCyB) rules that respond to real house prices or real household credit using the same central bank loss function as in the monetary policy experiment. The rules we study fluctuate around a long-run CCyB value of 2.5%. We find that although higher degrees of LAW by using time-varying CCyB lead to lower loss values, the reduction is negligible.

Related literature. Our analysis is closely related to a substantial body of literature on LAW policies, exploring the trade-offs in a model setting. Cúrdia and Woodford (2016) show that it is optimal for systematic monetary policy to react to financial frictions in reduced form. Gambacorta and Signoretti (2014) argue in favour of systematic LAW using a macro-financial DSGE model with a more elaborate financial sector as in Gerali et al. (2010). They find that supply shocks are amplified by the financial sector, in particular via asset prices, and a response of monetary policy to the latter lowers inflation volatility. We depart from these authors by explicitly differentiating between normal and crisis times and featuring persistent financial cycles. Caballero and Simsek (2020) analyzes prudential monetary policy in a stylized, three-period model with asset price booms and financial speculation. Their results show that monetary policy LAW can be beneficial in the case of an imperfect macroprudential policy setting. In a similar environment, Farhi and Werning (2020) study monetary and macroprudential LAW policies and find support for LAW-type monetary policy in the absence of a macroprudential policy instrument and under non-rational, extrapolative expectations. However, in addition to being highly stylized, neither of these models features supply shocks, which we show to play a crucial role in amplifying inflation fluctuations under LAW, leading to higher inflation volatility and rendering LAW not optimal.

Another influential study is Svensson (2017a). The paper evaluates nonsystematic LAW by monetary policy in a stylised Markov switching model of crises and normal times using a large-scale DSGE model for Sweden. LAW changes the probability, and severity of a crisis and has an impact on the economy in normal times. The paper concludes that LAW is not advisable, because the costs of implementing policy are far larger than the benefits. A key contribution of our work is to reconcile the previous two approaches and look at the contribution of nonsystematic and systematic policy in isolation and combination across normal and crisis times.

The contribution by Svensson (2017a) sparked further research into systematic LAW in Markov switching environments. Filardo and Rungcharoenkitkul (2016) and Ajello et al. (2019) use very stylized Markov switching NK models with minimalist representations of endogenous financial cycles and find LAW to be slightly beneficial. Nonetheless, the insights are limited by the reduced form modelling. Adding some more structure to the real economy side of the model but still using only an exogenous financial block, Gerdrup et al. (2017a) implement an OSR that generates (small) net benefits. While these three models do take into account the possibility of a crisis, the lack of an explicit modelling of the financial sector in these models is akin to assuming no financial frictions, which are shown to be crucial in Gambacorta and Signoretti (2014).

Svensson (2017b) summarises the criticism of DSGE models used to evaluate LAW policies. He highlights that these models do not incorporate: (i) the presence of the ELB; (ii) an explicit modelling of the financial sector, and (iii) the empirical moments and impulse responses observed in the data. Another key contribution of our work is that we respond to all of these criticisms. We set up a model with a fully fledged financial sector, building on Gerali et al. (2010), and endogenous crises calibrated to match historical crisis trajectories. Given this more realistic set up, and under rational house price expectations – which eliminate empirically relevant persistent financial cycles – we come to the same conclusion as the previously mentioned studies. However, if we account for persistent financial cycles under hybrid house price expectations, we find no evidence in favour of systematic LAW. Using a small-scale DSGE model with credit-fuelled financial crises, Gourio et al. (2018) find that in the presence of financial shocks, LAW by monetary policy is optimal. However, their model abstracts from persistent financial cycles, which proves key for the optimality of LAW policies.

More broadly, our study relates to the literature on the interaction of financial stability and monetary policy. Albertazzi et al. (2021) provides an overview and highlights the complex interactions of monetary and macroprudential policy in addressing financial stability risks. One such spillover is the risk-taking channel of monetary policy, by which an expansionary monetary policy stance can increase risk taking in the financial sector (see Adrian and Shin (2010), Dell'Ariccia et al. (2017)). Van der Ghote (2021) highlights the complementarity of macroprudential policy interventions at the effective lower bound. Using an empirical approach Bergant et al. (2020) also highlights the complementarities. They argue that tighter macroprudential policies allow monetary policy to respond more countercyclically to financial shocks.

The importance of the financial cycle is recognised and considered in Filardo and Rungcharoenkitkul (2016) and Kockerols and Kok (2021). The latter study also evaluates its influence on the results when assessing LAW policies and finds that considering the financial cycle attenuates the costs but concludes that LAW by monetary policy is not advisable. We contribute to this debate by quantitatively assessing the performance of systematic LAW policy in an endogenous RS framework with empirically plausible persistent financial cycles.

The rest of the paper is structured as follows. Section 1 describes the model briefly. Section 2 investigates systematic LAW using an endogenous RS DSGE model with ELB, crisis and asymmetric LAW regimes under persistent financial cycles. Section 3 concludes. We delegate the section on robustness checks to Appendix B.

1 The model

This section briefly describes the main features of the baseline constant-parameter version of NEMO. Readers may refer to Appendix D for model details. The regime-switching version of the model and the related elements specifically added for this paper such as crisis regimes, crisis probability and severity are detailed in Section 2.

NEMO is an estimated medium-scale New Keynesian DSGE model of a small open economy based on Norwegian data using Bayesian methods. The economy consists of households, a banking sector, intermediate goods producing firms, physical and housing capital producers, an oil sector, and a government including monetary authority. All agents have rational, or model-consistent, expectations with respect to all prices and quantities, except for households' house price expectations, which are partly backward-looking, as in Gelain et al. (2013).

NEMO features several real and nominal rigidities. These include habit persistence, investment adjustment costs, variable capacity utilization, and price and wage stickiness as in Smets and Wouters (2007). The model also incorporates collateral constraints based on loan-to-value ratios, long-term mortgage debt contracts, incomplete interest rate pass-through and capital requirements in the banking sector as in Iacoviello (2005), Gelain et al. (2017a), and Gerali et al. (2010).

Figure 1 provides a schematic illustration of the model and displays how the different sectors and agents are linked to each other. Households consume (C), work in the intermediate goods sector (L_I) and in the oil sector (L_O), buy housing services (H), borrow from banks (B_h) and save through deposits (D) as they derive utility from holding deposits.

The banking sector lends to households (B_h) and entrepreneurs (B_e), and is funded through deposits (D), foreign borrowing (B^*) and equity (K^B). An uncovered interest parity (UIP) relationship together with the country's net foreign debt position (private borrowing, B^*, minus

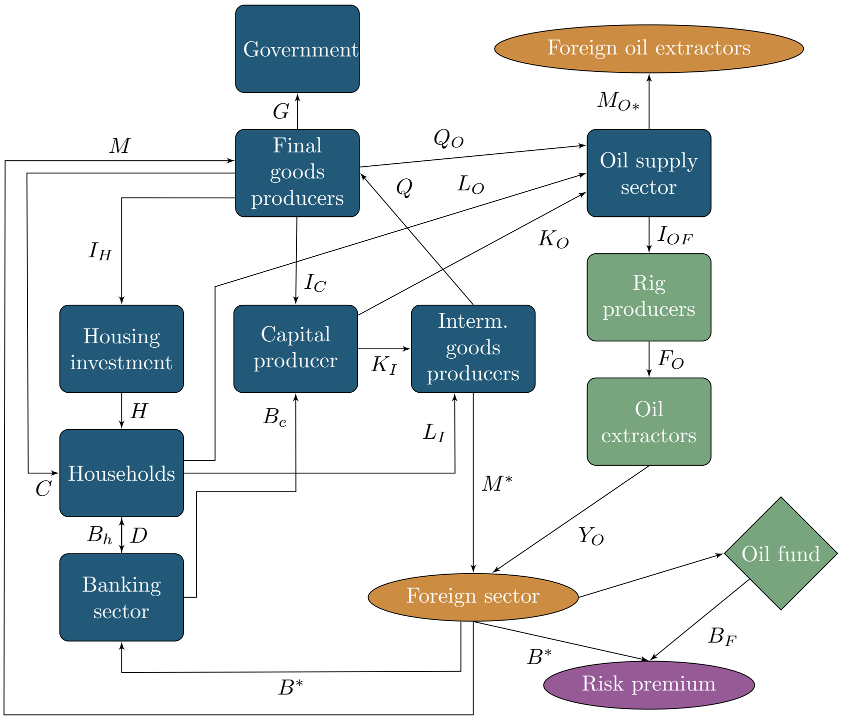

Figure 1: A bird's eye view of NEMO

government claims on foreigners, B_F) tie down the debt-elastic risk premium to ensure stationarity following Schmitt-Grohé and Uribe (2003).

Final goods producers bundle goods from domestic intermediate firms (Q) and imports (M). The final goods are used for household consumption (C), corporate investment (I_C), housing investment (I_H), government expenditures (G) and as inputs to the oil sector (Q_O). Intermediate goods producers employ labour supplied by households (L_I), rent capital from entrepreneurs (K_I) and sell their goods to the final goods producers (Q) and as export (M^*). The oil sector uses labour (L_O), capital (K_O) and final goods (Q_O) to produce oil supply goods that are exported (M_{O*}) or sold to the domestic rig producers (I_{OF}). The rig producers invest in oil rigs (F_O) to extract oil (Y_O) that in turn is exported in full. The profits are invested in the Government Pension Fund Global (GPFG), called the Oil fund in Figure 1.

The constant-parameter version of the model has been solved under optimal monetary policy with discretion (in normal, non-crisis times). However, when we conduct the analysis on LAW by monetary policy below, we use a "mimicking" policy rule that replicates the empirical properties of the baseline model without the possibility of crises under optimal policy. The reason is that solving optimal policy proves computationally expensive in the endogenous RS version of a large-scale DSGE model such as NEMO with eight different regimes while searching for optimal LAW policy. We show below that the mimicking policy rule we use provides a very good approximation to actual model dynamics under optimal policy.

The mimicking rule is an interest-rate feedback rule and a function of a number of variables such as price inflation, wage inflation, output, the real exchange rate, the money market premium and the lagged value of the nominal policy rate.[9] We employ an impulse response matching procedure to find the mimicking rule that replicates optimal policy. In particular, we find the response coefficients in the mimicking rule by matching impulse responses of a subset of variables[10] to a subset of shocks[11] under optimal policy for 10 periods.

The simple rule and the resulting response coefficients from impulse response matching are displayed in equation (1) and Table 1, respectively.[12] The variables in the mimicking rule include (in gap terms) annual inflation ($\widehat{\pi}_t$), expected annual inflation one quarter ahead ($\widehat{\pi}_{t+1}$), wage inflation ($\widehat{\pi}_t^W$), output ($\widehat{Y}_{NAT,t}$), the real exchange rate ($\widehat{S}_t$), the money market premium ($\widehat{Z}_{prem,t}$), the foreign monetary policy rate ($\widehat{R}_t^*$), a monetary policy shock ($Z_{RN3M,t}$) and a lagged term. When estimating the mimicking rule, we put higher weights on matching the responses on output, inflation and the policy rate to a monetary policy shock and an international oil price shock.

$$\begin{aligned} \widehat{R}_{P,t} = \omega_R \widehat{R}_{P,t-1} + (1-\omega_R)\left(\omega_P \widehat{\pi}_t + \omega_{P1}\widehat{\pi}_{t+1} + \omega_W \widehat{\pi}_t^W + \omega_Y \widehat{Y}_{NAT,t}\right. \\ \left. + \omega_S \widehat{S}_t + \omega_{PREM}\widehat{Z}_{prem,t} + \omega_{RF}\widehat{R}_t^*\right) + Z_{RN3M,t}. \end{aligned} \tag{1}$$

Table 1: Estimated mimicking rule

ω_R	ω_P	ω_{P1}	ω_W	ω_Y	ω_S	ω_{PREM}	ω_{RF}
0.74	0	1.45	0.82	0.30	0.02	-0.25	0

Note: Estimation results from an estimated policy rule that mimics optimal policy. The estimation hits the boundaries for ω_P and ω_{RF}.

[9] The mimicking rule was originally developed for estimation purposes since using optimal policy in the estimation process would be too time-consuming and computationally demanding.

[10] The evaluated variables are household credit, corporate credit, inflation, business investment, housing investment, oil investment, hours worked, imports, exports, output, house prices, the exchange rate, real wages and the policy rate.

[11] The shocks that are used in the impulse response matching comprise the monetary policy shock, money market premium shock, oil price shock, price markup shock, trading partner demand shock, risk premium shock, wage markup shock, labour supply shock, foreign marginal cost shock and foreign interest rate shock.

[12] The estimated mimicking rule in this paper slightly deviates from the one in Kravik and Mimir (2019) since we allow for a negative response to the money market premium in the current formulation.

Figure 2 shows the impulse responses to a monetary policy shock under optimal policy and the mimicking rule. The latter replicates arguably well the optimal monetary policy under discretion.[13]

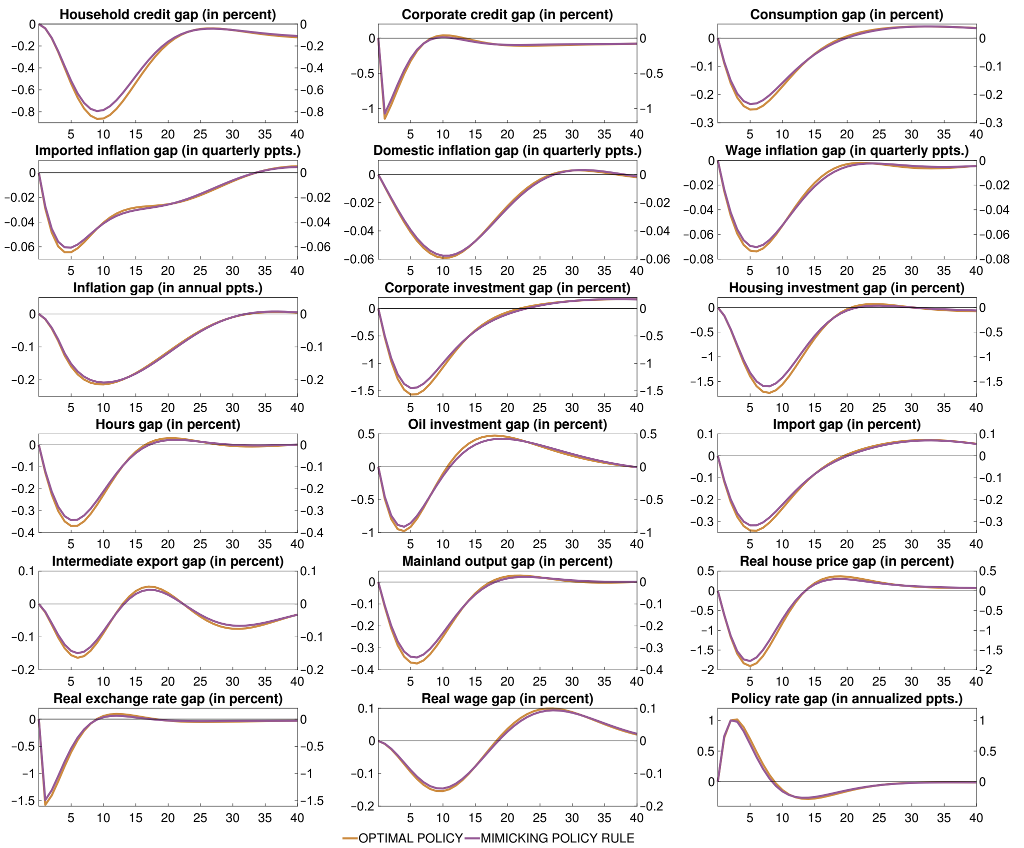

Figure 2: Impulse responses after a monetary policy shock under optimal policy and the estimated mimicking rule

The coefficients in Table 1 show that the mimicking rule found establishes a relatively high weight on wage inflation. This finding is consistent with Levin et al. (2006) who find that an interest rule responding to wage inflation yields a welfare outcome that nearly matches that under optimal policy, as well as Justiniano et al. (2011), who show that output gap stability is consistent with a significant reduction in the volatility of price and, especially, wage inflation.

We use this mimicking policy rule as our baseline monetary policy rule and evaluate systematic

[13] We also obtain similar results for the other structural shocks that are used in the impulse response matching exercise.

LAW policy in Section 2 against this rule. In particular, in the endogenous RS version of the model, we simply incorporate a response to real house prices into the mimicking rule above while assessing the plausibility of systematic LAW policy.

One of the criticisms laid out in BIS (2016) of the framework to analyse LAW proposed in Svensson (2017a) was that it does not take into account the persistence of the financial cycle. A way to include persistent financial cycles is to use hybrid expectations in house prices (Gelain et al., 2013). In fact, the DSGE model underlying our analysis features hybrid expectations in house prices. The inclusion is motivated by the findings of Gelain et al. (2013) that hybrid expectations enable the model to better capture the long cycles in house prices and household debt observed in the data. In other words, the model exhibits more persistent financial cycles similar to Farhi and Werning (2020).

Hybrid expectations are modelled as in Gelain et al. (2013). A share b^{sa} of households expects house prices to follow a moving average process (i.e. partly backward-looking expectations), whereas a share $(1 - b^{sa})$ has rational expectations (in log-gap form):

$$\mathbb{E}_t \left[\widehat{P}^H_{t+1}\right] = b^{sa}\widehat{X}^H_t + (1 - b^{sa})\widehat{P}^H_{t+1} \tag{2}$$

where $\widehat{\ }$ denotes gap-form and the moving average process is defined as:

$$\widehat{X}^H_t = \lambda^{sa}\widehat{P}^H_{t-1} + (1 - \lambda^{sa})\widehat{X}^H_{t-1}. \tag{3}$$

2 Systematic LAW in an endogenous RS-DSGE model

For the analysis of systematic LAW policy we conduct the experiments within the endogenous RS-DSGE framework with an ELB for the policy rate, financial crises, and asymmetric LAW in order to capture the effect of the changed decision rules of economic agents in the model as a result of systematic LAW policies. We further assume that the policymaker is aware of the possibility of a crisis and of how his or her actions can change the probability of the economy entering a crisis. The other economic agents underestimate the crisis probability.

We first describe how we model a financial crisis, how we incorporate the ELB into the model, and search for the optimal LAW policies given the possibility of crisis, and describe its quantitative properties. We then present the main results of our analysis of LAW policies. Finally, we show that two model ingredients prove to be crucial for the optimality of LAW among the many alternatives we considered in the section on robustness checks, appendix B. The first one is the persistence of financial cycles while the second one is the response to output in the monetary policy rule.

2.1 Crisis regime

Normal and crisis times are governed by a Markov process in the model. The probability and severity of crises are driven by household credit developments. The crisis path under systematic LAW policy is driven by a combination of shocks scaled by the size of financial imbalances and structural changes in the housing and financial sector.

2.1.1 The severity of a crisis

The crisis regime is calibrated to obtain a financial crisis that is similar to the macroeconomic scenario used in macroprudential stress-testing exercises at central banks. We replicate the dynamic paths of several macroeconomic and financial aggregates that are expected in a typical domestic financial recession. Furthermore, crisis episodes are also characterised by structural changes in the domestic economy: (i) money market and external risk premiums become more sensitive to changes in banks' capital positions; (ii) risk weights on household and business loans increase, and (iii) house prices and housing investment become more volatile.

We achieve this by translating the narrative to shocks hitting the economy in a crisis. Shocks to bank capital are used to capture credit supply shocks motivated by loan losses and asset write-downs observed during financial crises. Credit demand shocks, modelled using shocks to housing preferences, are motivated by the decline in household credit demand due to the fall in house prices and hence collateral values of houses. Shocks to domestic consumption demand are used to represent aggregate demand shocks. Last but not least, business investment-specific technology shocks replicate aggregate supply shocks motivated by a productivity slowdown observed during financial crises. We also consider the possibility that the CCyB is fully released in a crisis (set from 2.5% to 0%). The release of the CCyB reduces crisis severity by increasing banks' capacity to extend credit to households and non-financial firms during downturns.

In our model we want to capture the stylised fact that a buildup in financial imbalances precedes crisis episodes and the size of the imbalances correlate with the severity of the following crisis (see e.g. Borio and Lowe (2004). Therefore, the shock innovations for the structural shock processes outlined above consist of typical business cycle innovations and a crisis innovation:[14]

$$log(Z_t^i) = (1 - \rho^{Z^i})log(Z_{ss}^i) + \rho^{Z^i} log(Z_{t-1}^i) + \epsilon_{Z,t}^i - \beta^{Z^i} log(crisis_t) \tag{4}$$

where Z_t^i is a generic business cycle shock, Z_{ss}^i is the steady state (SS) level of the shock process, ρ^{Z^i} is the persistence parameter, $\epsilon_{Z,t}^i$ is the shock innovation, β^{Z^i} is a scale factor for each crisis shock innovation, $crisis_t$ is a shock, which is only active once the economy enters a crisis, and follows

$$log(crisis_t) = \rho_{crisis} log(crisis_{t-1}) + \Omega \kappa_t \tag{5}$$

where ρ_{crisis} is the persistence of the crisis shock. Ω is a crisis indicator variable. In normal times we have $\Omega = 0$, and in crisis times $\Omega = 1$. κ_t is a variable that captures the severity of crises. The severity, κ_t, is a function of credit imbalances, $B_{h,t}^{5y}$:

$$\kappa_t = (1 - \Omega)(\gamma + \gamma_{B_h} B_{h,t}^{5y}) + \rho_\kappa \Omega \kappa_{t-1} \tag{6}$$

where $B_{h,t}^{5y}$ is five-year cumulative real household credit growth, γ governs a constant effect of credit imbalances on the respective crisis shock and γ_{B_h} governs the effect of the initial level of credit imbalances on crisis severity. β^{Z^i}, ρ_{crisis}, γ, and γ_{B_h} are calibrated to match the asymmetric effect of a crisis on each crisis shock, the persistence of crisis shocks, the baseline severity and the additional severity of crises due to higher pre-crisis credit growth, respectively.

We calibrate the parameters for crisis severity, γ and γ_{B_h}, such that the model-based effect of pre-crisis credit growth on output during crises virtually matches, on average, the severity of the Norwegian banking crisis in the early 1990s. This is also in the range of the severity of different types of financial crises occurred in the European Union, described in Duca et al. (2017) in more detail and in Claessens et al. (2014) for the OECD countries. Figure 3 shows the dynamics of the output gap during financial crises in the model when pre-crisis five-year cumulative real

[14] A similar setup is used in Gerdrup et al. (2017a).

household credit growth is at its average (solid line) and when it is one standard deviation (SD) higher than its average (dashed line).

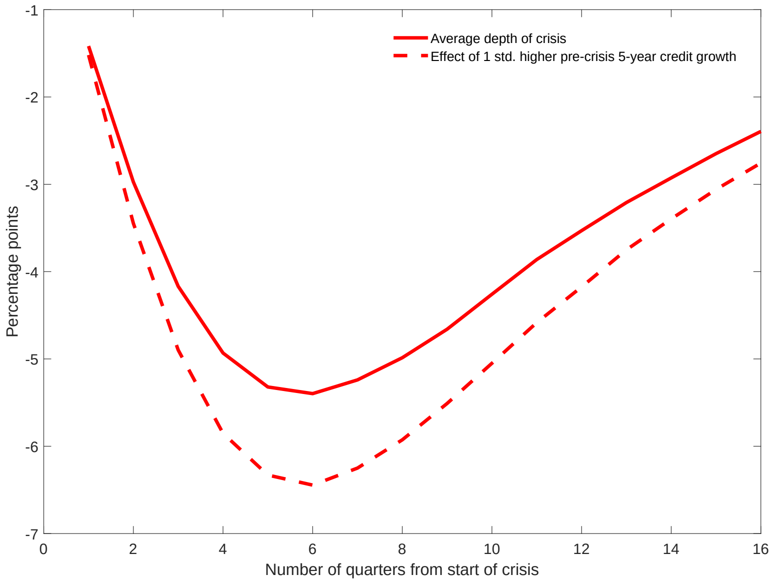

Figure 3: Dynamics of output gap during financial crises

The figure indicates that output falls by 5.4% on average at its lowest point during a financial crisis when pre-crisis credit growth is at its average. However, when pre-crisis credit growth is one SD higher than its average, output declines by about 6.45% at its lowest point. Considering that the SD of five-year cumulative growth in real household credit is 12.3% , output declines by $1.05/12.3 = 0.085$ percentage point (pp) more on average during financial crises if five-year cumulative real credit growth is 1 pp higher before the crisis. This elasticity is consistent with those found in Jordà et al. (2013) and Gerdrup et al. (2017a). Moreover, the effect of a financial crisis on output is highly persistent because output is still below its pre-crisis level even two years after the end of the crisis (given that the average duration of a crisis is two years). This is in line with the notion that the recoveries after financial crises are very slow due to the scarring effects of such crises on the real economy.

2.1.2 The probability of a crisis start

The probability of being in a crisis is determined, assuming a Markov process, by the probability of a crisis start and the crisis duration. We assume the crisis duration to be eight quarters, which reflects the mean unfiltered peak to trough duration of the financial cycle in Europe as defined in Schüler et al. (2015).[15]

Schularick and Taylor (2012), Jordà et al. (2013), and Mian and Taylor (2021) argue that credit developments increase both the probability and severity of crises.[16] We also rely on five-year credit growth as a proxy for both the probability and severity of a crisis, and this choice is empirically supported by Arbatli-Saxegaard et al. (2020), who find that five-year credit growth has the most significant effect on downside risks to output growth in Norway. Underlying the quarterly probability of a crisis start is a logistic function that links the policy impact via five-year cumulative growth in real household credit to the probability of a crisis start.[17] We use an estimated logistic regression for the (quarterly) probability of a crisis start, q_t: $q_t = 1 - \frac{1}{1+\exp(4.792-2.232D_t^{\Delta 5Y})}$, on five-year cumulative growth in real household credit, $D_t^{\Delta 5Y}$, based on a sample of twenty Organisation for Economic Co-operation and Development (OECD) countries over the period 1975Q1 - 2014Q2. We also conduct a robustness check by using an estimated crisis start probability function that depends on five-year cumulative growth in real house prices. The estimated parameter values are given in Table 2.

Table 2: Estimated parameters in the logit model

	Probability of crisis start	
Five-year cum. growth in real household credit	2.232**	
	(1.099)	
Five-year cum. growth in real house prices		1.896***
		(0.607)
Constant	-4.792***	-4.804***
	(1.026)	(1.005)
Country fixed effects	Yes	Yes
Pseudo R-Squared	0.0424	0.0348
AUROC	0.666	0.688
Observations	1832	2070

Notes: Significance levels: *10%, **5%, ***1%.

Figure 4 plots the annualised crisis start probabilities as a function of either real household credit growth or real house price growth. The probability of a crisis start increases from 3.3% to 4.85%

[15]The crisis duration of eight quarters is to be seen in combination with the 5 pp reduction in output. Taken together, 10 pp-years of output deviation determine the severity of the crisis in the model.

[16]Grimm et al. (2023) provides empirical evidence based on 150 years of data for 18 advanced economies that monetary policy that is expansionary for an extended period of time tends to be followed by periods of financial instability.

[17]See Ajello et al. (2019) and Gerdrup et al. (2017a) for other examples where they use household credit growth as a proxy for crisis severity and probability.

when five-year cumulative real household credit growth is one standard-deviation (17%) higher.[18]

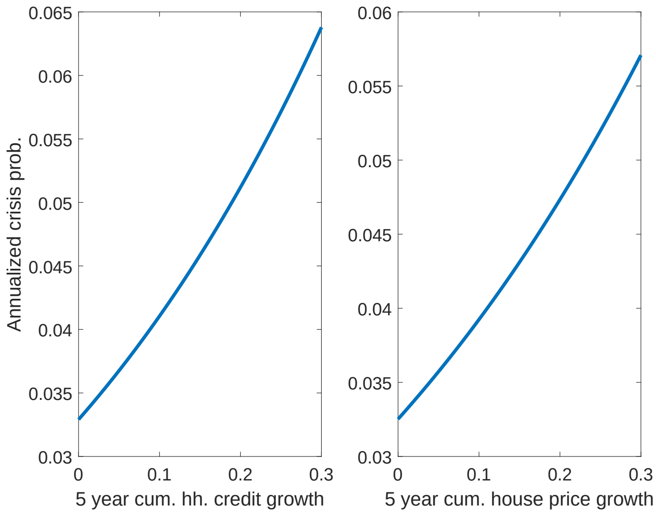

Figure 4: Crisis probability function

Using a simple linear approximation[19], these values imply an SS probability of being in a crisis of around $p_t = 6\%$. The quarterly probability of a crisis start is used in both parts of the analysis as outlined above.

We rely on the linking function outlined above with one important modification. When we simulate the model, we truncate the probability of a crisis such that the economy does not enter into a crisis when five-year cumulative credit growth (or house price growth) is below zero.[20] We also conduct a robustness check using five-year cumulative real house price growth as an input into the crisis probability function.

The setup of the probability of a crisis imply an annualised probability of a crisis start of 3.3% and a probability of being in a crisis of 7%.

[18] Svensson (2017a) estimated an annualised probability of a crisis start of 3.2% based on a linking function using a database of 14 developed countries for 1870-2008 (Schularick and Taylor, 2012).

[19] The linear approximation is the sum of the quarterly probabilities of a crisis start over eight quarters: $p_t \approx \sum_{i=0}^{n-1} q_{t-i}$.

[20] In order to match the estimated SS annual probability of a crisis start of 3.3% in our model on average while truncating the probability of a crisis, we re-calibrated the constant term in the estimated logit function that is used in the model and we set it to -4.25.

2.2 Optimal simple rule through the cycle, ELB on nominal interest rates and asymmetric LAW

We assume that the central bank has the following operational loss function when setting the policy rate:

$$\min_{\widehat{R}_{P,t}} \mathbb{E}_t \sum_{t=s}^{\infty} \beta^{t-s} \left[(\pi_t - \pi^*)^2 + \lambda_y \widehat{y}_t^2 + \lambda_{dr} \left(\triangle R_{P,t} \right)^2 \right] \tag{7}$$

where β is the household's discount factor, π_t is the inflation rate, π^* is the inflation target, $\widehat{y}_t$ is the output gap, $\triangle R_{P,t}$ is the change in the nominal policy rate, λ_y is the weight on the output gap, and λ_{dr} is the weight on the change in the nominal interest rate.[21]

Monetary policy rules we consider incorporate the possibility of an ELB and asymmetric LAW. The ELB is modelled as a regime switch where the switching parameter is governed by a Markov chain (Ω_{zlb}) with two regimes, a positive policy rate regime and an ELB regime, given by

$$R_{P,t} = (1 - \Omega_{zlb}) R_{P,t}^{shadow} + \Omega_{zlb} R_{P,t}^{zlb} \tag{8}$$

where $R_{P,t}$ is the actual policy rate, $R_{P,t}^{shadow}$ is the shadow rate given by the estimated mimicking rule modified to respond to real house prices as well and $R_{P,t}^{zlb}$ is the ELB interest rate, which we set to 1.

The probability of switching to an ELB regime is a function of the distance between the shadow policy rate and the policy rate at the ELB and is given by a step function. When the shadow policy rate is greater than the policy rate at ELB, the probability of switching is zero and equal to one otherwise. The way we implement ELB resembles that in Aruoba et al. (2017). When the economy switches to an ELB regime, we assume that the new regime has a zero SS inflation rate compared to a 2% SS inflation rate in a positive policy rate regime.[22] We choose to model the

[21] We set λ_y to 0.3, which is similar to the standard values in the literature and is lower than that for inflation. In addition, the change in the nominal interest rate incorporated into the loss function (the last term in Equation (7)) ensures that the current policy rate does not deviate excessively from the policy rate in the previous period, hence it corresponds to the interest rate smoothing (inertia) in a standard Taylor-type interest rate rule. Therefore, it induces a gradual adjustment of the interest rate in response to changes in inflation and output gap.

[22] Implementing an ELB in a DSGE model introduces an interesting non-linear problem in an open economy framework due to the asymmetry it induces in interest rates in the domestic economy and abroad. In particular, a fixed nominal interest rate (of zero) violates the UIP condition in SS that the domestic real interest rate must be identical to the real interest rate abroad (conditioned on a zero risk premium in SS). Instead of having a lower SS inflation rate in the ELB regime, two alternative ways of solving this challenge include either a) to introduce a non-zero risk premium in SS, or b) also letting the nominal interest rate abroad go to zero in the SS. Our choice of implementing the ELB here does not drive our results. Binning and Maih (2016) discuss various ways of implementing an ELB within a simple closed-economy RS DSGE model.

ELB in this way since we think it is empirically consistent with the persistently lower inflation observed in most major advanced economies after the GFC. We also find it reasonable to assume lower SS inflation in the ELB since we do not consider unconventional monetary policy within the model and the central bank has no other tools to raise the inflation rate in this deflationary state of the world.

We evaluate systematic LAW by augmenting the mimicking rule to include a response to the real house price gap. The reason why we use real house prices is based on Svensson (2013), who argues that the stock of debt (especially mortgages with long maturities) has substantial inertia and monetary policy has little effect on it whereas it has more effect on the growth of house prices. However, we also conduct a robustness check using real household credit gap in the mimicking rule.

$$\widehat{R}_{P,t}^{shadow} = \omega_R \widehat{R}_{P,t-1}^{shadow} + (1-\omega_R)\Big(\omega_P \widehat{\pi}_t + \omega_{P1}\widehat{\pi}_{t+1} + \omega_W \widehat{\pi}_t^W + \omega_Y \widehat{Y}_{NAT,t} + \omega_S \widehat{S}_t + \omega_{PREM}\widehat{Z}_{prem,t} + \omega_{RF}\widehat{R}_t^*\Big) + (1-\Omega)\mathbb{1}_{\widehat{P}_{h,t}>0}\omega_{PH}\widehat{P}_{H,t} + Z_{RN3M,t} \tag{9}$$

where $\widehat{R}_{P,t}^{shadow}$ denotes the shadow rate gap, and $\mathbb{1}_{\widehat{P}_{h,t}>0}$ is an indicator function which reflects asymmetric LAW.

We consider an asymmetric interest rate rule that responds to a real house price gap only when the gap is positive.[23] The motivation behind it is that LAW policies are usually implemented when financial imbalances are high. Monetary policy is tighter than what is consistent with inflation and output stability when credit imbalances are higher than a certain threshold value, which is assumed to be zero.[24] We also assume that monetary policy does not respond to house prices during crises.[25] Asymmetric LAW is implemented as another regime, with the indicator function $\mathbb{1}_{\widehat{P}_{h,t}>0}$ governing the Markov process. Note that this regime switch interacts with the switching parameter Ω for the crisis regime such that LAW is only relevant when the economy is

[23] A similar formulation of an interest rate rule can be found in Gerdrup et al. (2017a).

[24] We also conduct robustness checks by changing the threshold value of reacting to a real house price gap in the mimicking rule from zero to positive values but it does not change the main results of the paper.

[25] We specifically assume that monetary policy does not respond to house prices during crises since we wanted to confine our analysis particularly to the leaning-against-the-wind (LAW)-type monetary policy rules that implies a somewhat tighter policy rate than what is consistent with flexible inflation targeting mandates of inflation and output stabilization. One can also consider (or even combine LAW with) the "mopping after crash" type policies that respond to house prices (or to financial variables in general) during financial crises episodes within our framework, which we left for future research.

not in a crisis and the real house price gap is positive.[26]

Overall, the model features eight regimes, each a combination of three two-state Markov chains: normal vs. crisis times, positive policy rate vs. ELB and no LAW vs. LAW. We then choose ω_{PH} to minimise the operational loss function defined in equation (7) in the model including all components mentioned above, holding all other response coefficients fixed at their previously estimated levels. We only optimise over ω_{PH} since we want our interest rate rule to reflect the actual monetary policy stance of the central bank and not to deviate too much from its current inflation and output stabilisation objectives following Gelain et al. (2013) and Gourio et al. (2018). Moreover, we assume that all the economic agents in the model are aware of the possibility of switching to the ELB and LAW regimes but they underestimate the probability of crisis regime, meaning that they attach a zero probability to switching to a crisis regime. The only exception is the central bank since it is aware of the possibility of crises at all times, and it decides whether to respond to real house prices to prevent financial crises from happening. Furthermore, in Section B, we explore the individual contributions of asymmetric LAW and the ELB by doing the same analysis without them – among many other robustness checks.

2.3 Quantitative properties of the RS DSGE model

2.3.1 Time spent in different regimes

The benchmark model with the possibility of crises and ELB features four regimes: No crisis-No ELB, No crisis-ELB, Crisis-No ELB, and Crisis-ELB. To compute the time spent in each regime over the business cycle, we simulate the model for 100,000 periods. We find that the economy spends 72% of the time in No crisis-No ELB regime. The simulations also show that 21% of the time is spent in No crisis-ELB regime. This number is close to the unconditional probability of being in the ELB regime estimated for the U.S. economy by Aruoba et al. (2017). Moreover, we observe that the economy spends 3% of the time in Crisis-No ELB regime and 4% of the time in Crisis-ELB regime.

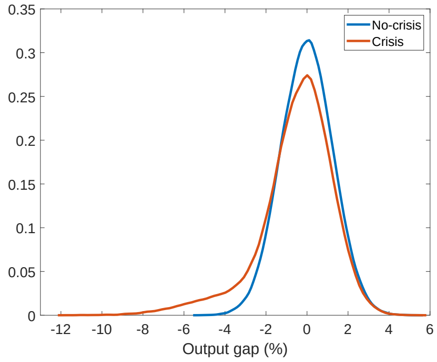

Figure 5: Downside risks to GDP: No-Crisis vs. Crisis

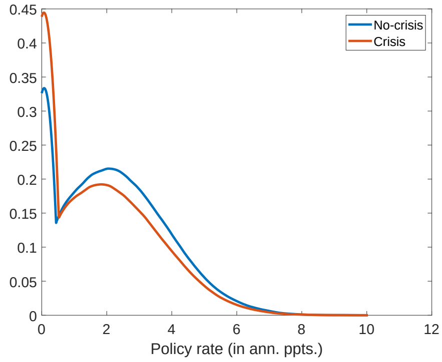

Figure 6: Downside risks to policy rate: No-Crisis vs. Crisis

2.3.2 Downside risks to output

Figures 5 and 6 show the distributions (kernel densities) of the output gap and policy rate in the models with and without crisis (solid red and blue lines, respectively). In both models, the ELB may bind. As expected when using linearisation, the distribution of the output gap in the model with no-crisis is virtually symmetric around zero, indicating no asymmetric tail risks either for the upside or for the downside. The left fat tail in the distribution under crisis displays significant downside risks to GDP while there are no upside risks. This is expected given the negative asymmetric crisis shocks and RS structural parameters in the housing and banking sectors. The results are also in line with the Growth-at-Risk (GaR) literature pioneered by Adrian et al. (2019). They show how current financial conditions can affect downside risks to future GDP growth. Finally, the distribution of the policy rate in the models with and without crises shows that the ELB binds more often in the model with crisis due to more downside risks in inflation and output (see Figure 5).

2.3.3 Dynamics of financial crises

Figure 7 shows the distribution of the behaviour of main macroeconomic and financial variables when the economy enters into a crisis. We simulate the model for 100,000 periods and collect the dynamics of the variables of interest in crisis regime. We obtain 836 crisis episodes with an average duration of 8.4 quarters each and produce the fan chart below. The black dashed-lines display the median behaviour while the other shaded areas show the 30^{th}, 50^{th}, 70^{th},and 90^{th}

[26]Instead of an asymmetric policy rule as described, one can also consider an asymmetric loss function that puts more weight on output stabilization during crises compared to normal times as central bank preferences could shift during these episodes. Our framework is also suitable to conduct such an analysis.

percentiles.

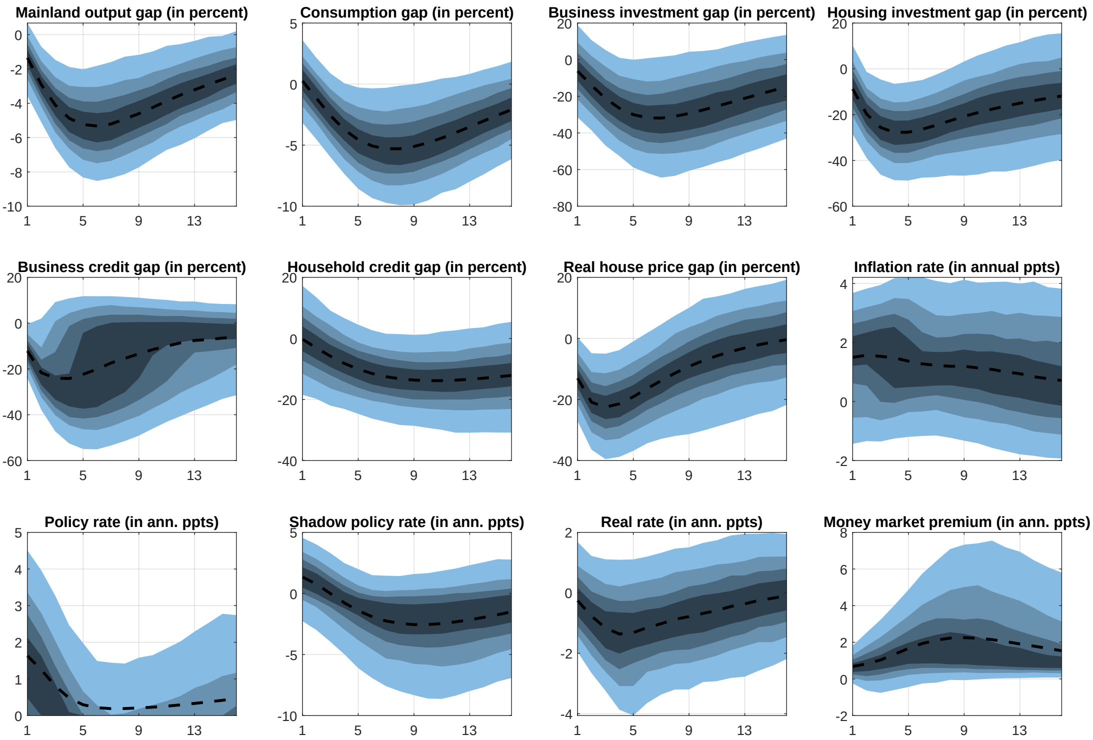

Figure 7: Different percentiles of main macroeconomic variables in a financial crisis

The economy is hit by asymmetric large crisis shocks, i.e. shocks to bank capital, housing preferences, domestic consumption demand and marginal efficiency of investment in addition to typical estimated business cycle shocks when a financial crisis unfolds. Moreover, the banking and housing sectors become more sensitive to these shocks due to the structural changes in those sectors during a crisis. Since the money market premium, which affects the cost of funds for banks, is affected by changes in banks' capital positions during crises, a shock to bank capital leads to an average 200 basis points (bp) increase in the premium, but in extreme crisis it can be four times larger. As a result, lending spreads also rise about 200 bp on average in annual terms. This on average causes household credit to decline by about 15% and business credit to fall 25% – so business and housing investment shrink by some 30% on average, while mainland output and consumption fall about 5% on average. In the least severe crisis, output falls by about 2% at the peak, while it declines by around 8% in the most severe crisis. The inflation rate decreases by 1.5 pp to 0.7% on average but there are crisis episodes where inflation can be negative. The shadow policy rate declines by 3 pp in annualised terms, entering negative territory. Due to the ELB on the nominal policy rate, the actual rate stays positive, putting a drag on the economy, which we show in B. In that section, we also present how the release of the CCyB during a crisis mitigates the adverse effects of crises on macroeconomic and financial variables.

2.3.4 Model moments under different regimes

Table 3 displays the second moments of some selected model variables, loss values relative to the benchmark model (the model with crises and ELB imposed), and annualized frequencies of crisis for the models with crisis and ELB imposed, with crisis, ELB imposed and CCyB relaxed, with crisis and no-ELB and with no-crisis and ELB imposed under the baseline mimicking policy rule.

Table 3: Model moments with and without crisis under baseline mimicking rule

Moments (%)	Crisis (ELB)	Crisis (ELB and CCyB released)	Crisis (No-ELB)	No-crisis (ELB)
SD Annual inflation	1.11	1.11	1.14	1.08
SD Output gap	1.89	1.84	1.79	1.25
SD Interest rate (Ann. %)	1.31	1.31	2.21	1.44
SD Real exchange rate	5.34	5.27	5.38	4.97
SD Household credit	12.3	12.1	11.9	12.0
SD Real house prices	13.2	12.9	12.9	11.9
Relative Loss	100	99.7	98.7	96.0
Prob. of crisis start (Ann. %)	3.34	3.33	3.27	0.00

Notes*: Model SDs and the frequency of financial crises are computed from 100,000 simulations. The loss function is given by equation (7). We take $\beta = 0.99$ and the weights on the output gap and the change in the nominal interest rate is $\lambda_y = 0.30$ and $\lambda_i = 0.40$, respectively.*

A comparison of the second and the fifth columns shows that incorporating financial crises into the model increases the volatilities of macroeconomic and financial variables, as expected. The crisis regime has the largest effect on output, house prices and the real exchange rate. The presence of the ELB in the models with crises increases the volatilities of all variables except inflation and the real exchange rate. The loss value is also higher when the ELB binds. Moreover, the CCyB release contributes to more stable output, house prices, household credit and the real exchange rate.

2.4 Systematic LAW under hybrid house price expectations

In this section, we investigate the effect of different degrees of systematic LAW by monetary policy in the model outlined above featuring hybrid house price expectations (hence persistent financial cycles). To this end, we run a discrete grid search over the response coefficient of the real house price gap in the estimated mimicking rule (ω_{pH} in equation (9)) over the interval [-0.02 0.05], using a step-size of 0.0025. We hold all other response coefficients in the mimicking rule constant at their previously estimated values in the model without the possibility of crises. Holding the other coefficients constant allows us to compare the outcome for different degrees of LAW. It would be close to impossible to isolate the effect if all coefficients were to change. For each of the 29 grid points, we simulate the economy for 100,000 periods. We evaluate the optimal degree of LAW by minimising the loss function shown in equation (7).

Different values of ω_{pH} translate into different levels of LAW in the monetary policy stance. For example, $\omega_{pH} = 0.05$ would mean that, all else equal, a positive real house price gap of 10% on average would increase the annualised policy rate by 200 bp on average. Our grid point step-size corresponds to 10 bp, given an average positive real house price gap of 10%.

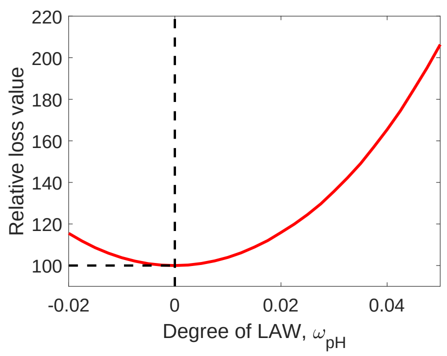

Figure 8: Relative loss values for different degrees of LAW

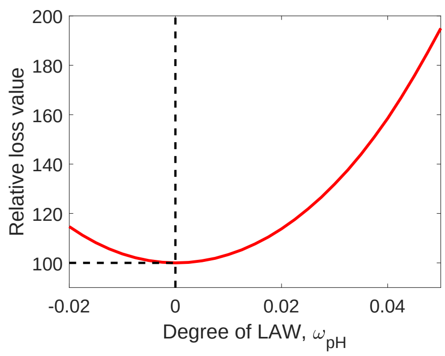

Figure 9: Relative loss values for different degrees of LAW in the model without crisis

Figure 8 shows the loss values corresponding to different degrees of LAW (different ω_{pH} coefficient values) relative to the loss in the model without LAW. We obtain the lowest loss value when $\omega_{pH} = 0$, i.e. no LAW. The loss value increases substantially with a higher degree of LAW.

This result is not trivial because we start from a policy rule mimicking optimal policy in the single regime case. The addition of seven more regimes makes it unlikely to be optimal and our results suggest that contrary to our prior idea, it remains optimal not to lean against the wind even when a crisis and the ELB are included.

Figure 9 shows the relative loss when there is no crisis regime. We still find that LAW is not optimal. Although the relative loss values are lower overall in the model without the possibility of crises, as expected, a positive degree of LAW is still not preferred.

2.4.1 Understanding the results

We can decompose the central bank loss function into expected gaps and variances of inflation, output and policy rate changes as follows.

$$L_t = \sum_{t=s}^{\infty} \beta^{t-s} \Big((\mathbb{E}_t[\pi_t - \pi^*])^2 + \lambda_y (\mathbb{E}_t[\widehat{y}_t])^2 + \lambda_{dr} (\mathbb{E}_t[\triangle R_{P,t}])^2 + \text{Var}_t[\pi_t] + \lambda_y \text{Var}_t[\widehat{y}_t] + \lambda_{dr} \text{Var}_t[\triangle R_{P,t}] \Big) \tag{10}$$

The first three terms in equation (10) denote the expected gaps of inflation, output and policy rate changes. The expected central bank loss is higher under larger gaps in these variables. The last three terms are the variances of inflation, output and policy rate changes. This means that higher volatilities in these variables lead to greater central bank loss. We evaluate how LAW-type monetary policy rules change these different components of the central bank loss function.

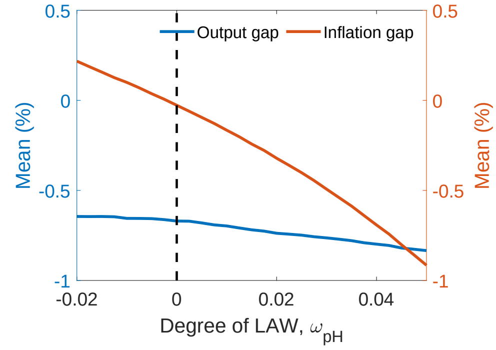

Figure 10: Expected gaps under different degrees of LAW

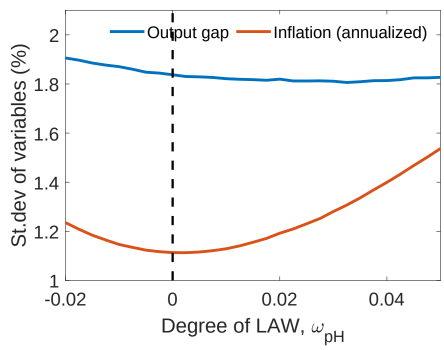

Figure 11: SDs under different degrees of LAW

Figure 10 shows how the expected inflation gap and output gap change under different degrees of leaning. We do not depict the expected change in the policy rate gap since it is relatively small and will not substantially change the central bank loss. The figure indicates that the expected inflation gap falls with a higher degree of LAW. The expected output gap also decreases but only to a limited extent. An increase in the policy rate due to a positive degree of LAW leads to a decline in both inflation and output, contributing to higher losses in terms of the first two terms in (10). The figure also shows that when the degree of LAW is zero, the expected inflation gap is virtually zero while the expected output gap is already negative.[27] This results from the downside risks to output stemming from financial imbalances, which is also depicted in the left-skewed distribution of output depicted in Figure 6. The results indicate that the gains in terms of higher output due to lower downside risks under LAW-type monetary policy are not enough to compensate for the decline in output in normal times due to higher interest rates.

Figure 11 shows how inflation and output volatility change with varying degrees of LAW. Inflation volatility increases significantly while the output volatility falls only slightly under higher degrees of leaning. This result stands in contrast to Alpanda and Ueberfeldt (2016), who find that both output and inflation volatility decrease with positive degrees of LAW. Although LAW policies reduce the downside risks to the economy, the fall in these risks due to LAW-type monetary policy is highly limited, resulting in a small reduction in the output volatility. This finding also indicates that the inflation variability is the main driver of higher losses. For a deeper understanding of the results, it is fruitful to study the costs and benefits of leaning separately.

Benefits of LAW The main benefits of leaning potentially involve lower crisis probability and reduced crisis severity. Figure 12 shows how much time the economy spends in the Crisis-No ELB, Crisis-ELB, and crisis regimes.

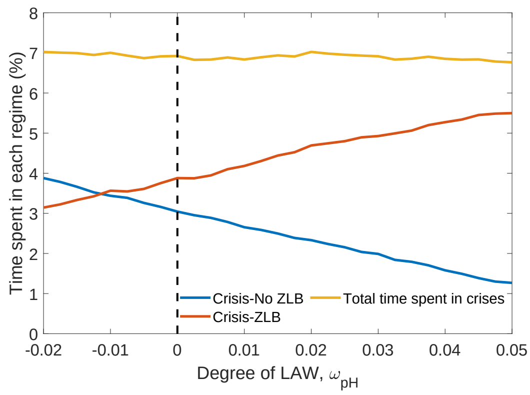

Figure 12: Time spent in a crisis regime

The figure shows that the time the model economy spends in Crisis-No ELB regime declines under higher degrees of LAW, while the time spent in the Crisis-ELB regime increases. The

[27]The effects of crises on inflation are not as clear as their unambiguously adverse impact on output because while inflation may fall due to lower domestic demand in crises, it may also rise due to the exchange rate depreciation in these episodes. Figure 7 shows that it is equally likely that inflation can be either positive or negative, depending on the strength of these two opposing forces.

increase in time spent in Crisis-ELB regime is due to the fact that higher degrees of LAW lead to an initially higher interest rate, pushing down inflation and the interest rate with it until it reaches the ELB.

The total time spent in a crisis regime declines slightly with higher degrees of LAW. For nonsystematic LAW, we also found that the probability of a crisis start moves only to a small extent and it decreases only slightly on average over a longer term horizon (see Figure 55). Therefore, we conclude that the additional effect of changed decision rules due to systematic policy does not substantially change the effect on the probability of a crisis start.

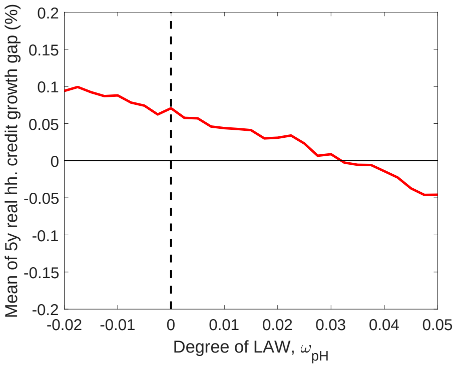

Figure 13: Mean of 5-year credit growth gap and degree of LAW in normal times

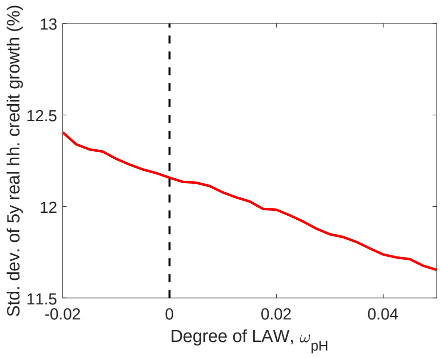

Figure 14: SD of 5-year credit growth and degree of LAW in normal times.

Remember that crisis probability depends on pre-crisis five-year cumulative real household credit growth. Figures 13 and 14 show how the mean and SD of five-year cumulative real household credit growth gap change in normal times as the degree of LAW increases. They indicate that higher degrees of LAW reduce both the mean and the volatility of financial imbalances measured by five-year credit growth, but the reduction is quite limited. This explains why the probability of crisis falls only slightly under higher degrees of leaning.

Figure 15 displays the average dynamics of the output gap during financial crises in the model simulations under no-LAW (blue solid line) and LAW (orange solid line). We choose a response coefficient of 0.05, which corresponds to a 200 bp higher policy rate on average if the real house price is 10% higher than its SS value. The figure shows that LAW effectively limits the drop in the output gap during crises (i.e. output during crisis compared to time of crisis start). Output falls by 5% after six quarters without LAW while it declines by a little more than 4% with LAW. Although the average crisis duration is 8.4 quarters, it takes even longer for the output to recover

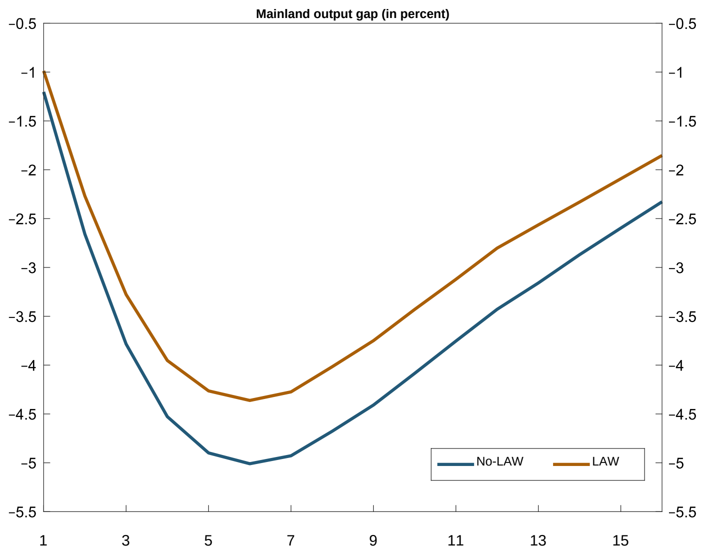

Figure 15: Average behaviour of output gap in financial crises. With LAW (orange line, $\omega_{pH} = 0.05$) and without LAW (blue line, $\omega_{pH} = 0$). Percentage change compared to time of crisis start.

to its pre-crisis levels under no-LAW due to the longer-lasting effects of crises.

Costs of LAW The main costs of LAW-type monetary policy are lower levels of inflation and output in normal times, higher inflation volatility and a higher likelihood of hitting the ELB. The latter potentially results from lower average inflation, leading to a lower nominal policy rate in the long-run. It also contributes to higher inflation volatility in the model.

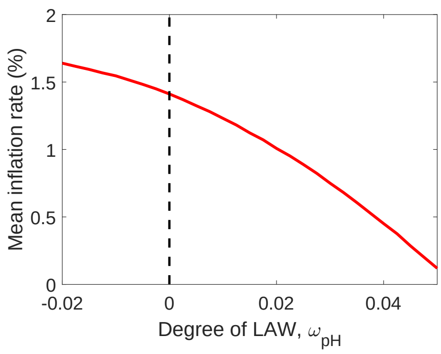

Figure 16: Inflation in normal times.

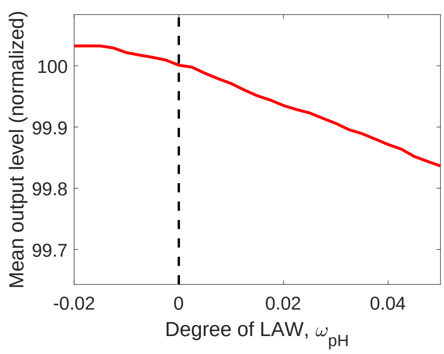

Figure 17: Output in normal times.

Figures 16 and 17 display the means of inflation rate and output level in normal times for various degrees of LAW.

Figures 18 and 19 display the inflation and output volatility for different degrees of LAW in normal times. As per higher degrees of LAW, the inflation volatility increases substantially while

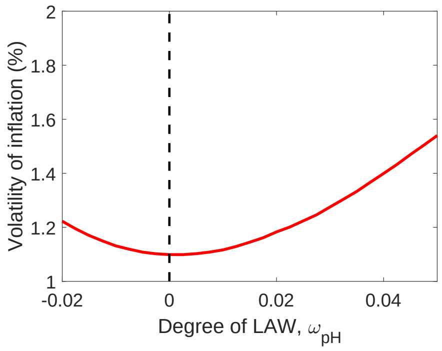

Figure 18: SD of inflation in normal times.

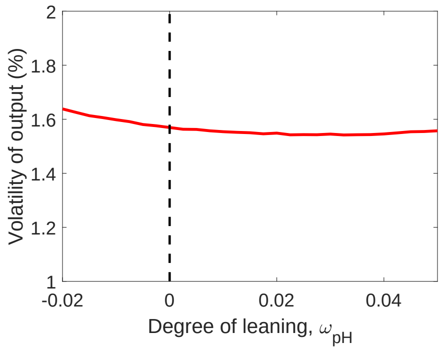

Figure 19: SD of output in normal times.

output volatility falls only marginally. The former significantly contributes to higher loss values, making the optimal degree of LAW zero.

The decomposition of the effects of LAW on inflation and output volatility into those in normal times only (see Figures 18 and 19), and those in normal plus crisis times (see Figure 11) shows that the overall effect is driven by higher inflation volatility in normal times.

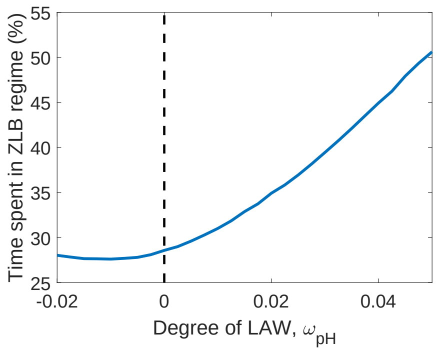

Figure 20: Time spent in ELB episodes for various degrees of LAW

Figure 20 shows how the time spent in ELB periods alters under different degrees of LAW. A higher response coefficient makes the economy more vulnerable to the ELB since it reduces the mean nominal policy rate by lowering the mean inflation rate. The time spent at the ELB increases from about 28% to nearly 50% under an aggressive LAW policy. A higher probability of hitting the ELB also contributes to higher inflation volatility, increasing losses further.

To develop a better understanding of the increase in the inflation volatility due to LAW, we plot the impulse responses to one SD wage markup and import demand shocks in Figures 21 and 22. These two shocks explain significant fractions of the variations in inflation and output over the business cycle. The impulse responses belong to normal times since the economy spends 76% of the time there.

Under the baseline-mimicking policy rule, a negative wage markup shock lowers the market power of employees and leads to workers being able to exercise less market power, generating downward pressure on wages. The drop in wages causes firms' marginal costs and prices to fall. In response to the decline in inflation, the central bank lowers the short-term policy rate. Despite a temporary reduction in real wages, consumption increases due to lower interest rates. This also causes investment expenditures to go up, increasing aggregate demand. The drop in the policy rate also generates a real exchange rate depreciation. This results in higher export volumes. Although the real exchange rate depreciation is expected to lower imports, higher consumption demand dominates this effect and leads to higher imports. Credit and house prices increase alongside the overall favourable macroeconomic environment.

As expected, the LAW-type policy rule dampens real house prices compared with the baseline-mimicking rule. This provides less collateral value for households and hence dampens the increase in household credit and in consumption. It also prevents both business and housing investment from rising as much as is the case under the baseline policy rule. Therefore, the increase in output is not as strong. However, this restraining effect on domestic demand of LAW policies also results in more negative responses in inflation, and hence worsens the trade-off between inflation and output stabilisation. When we search for the optimal LAW policy, this trade-off is resolved in favour of not leaning either way. A similar line of reasoning also applies under the import demand shock, where the increase in the inflation rate under LAW is more pronounced compared with very limited output stabilisation.

2.5 Systematic LAW under rational house price expectations

In the following, we redo the previous experiment but this time with rational expectations in house prices (by setting $b^{sa} = 0$ in equation (2)), leading to less persistent financial cycles. We first estimate the mimicking rule in the baseline constant-parameter version of NEMO with rational expectations in house prices. We then search for the optimal response coefficient to real house prices in the RS version of the model with the same rational expectations by holding all other response coefficients fixed at their previously estimated levels as in the previous section.

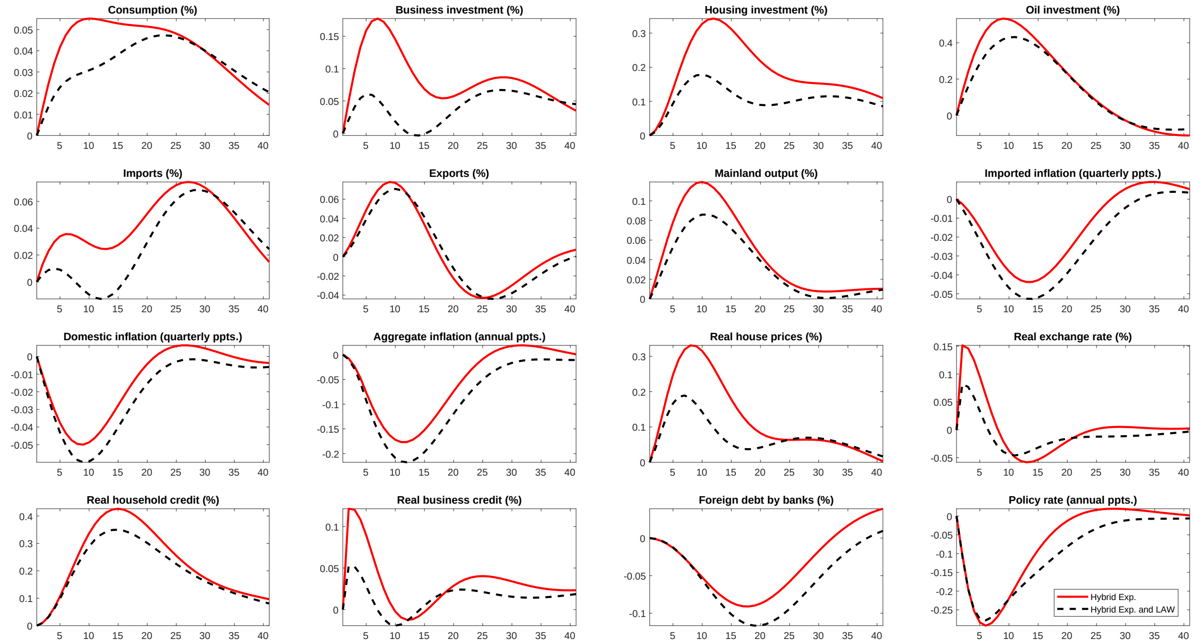

Figure 21: Impulse responses after a one SD wage markup shock with and without LAW under hybrid expectations in house prices

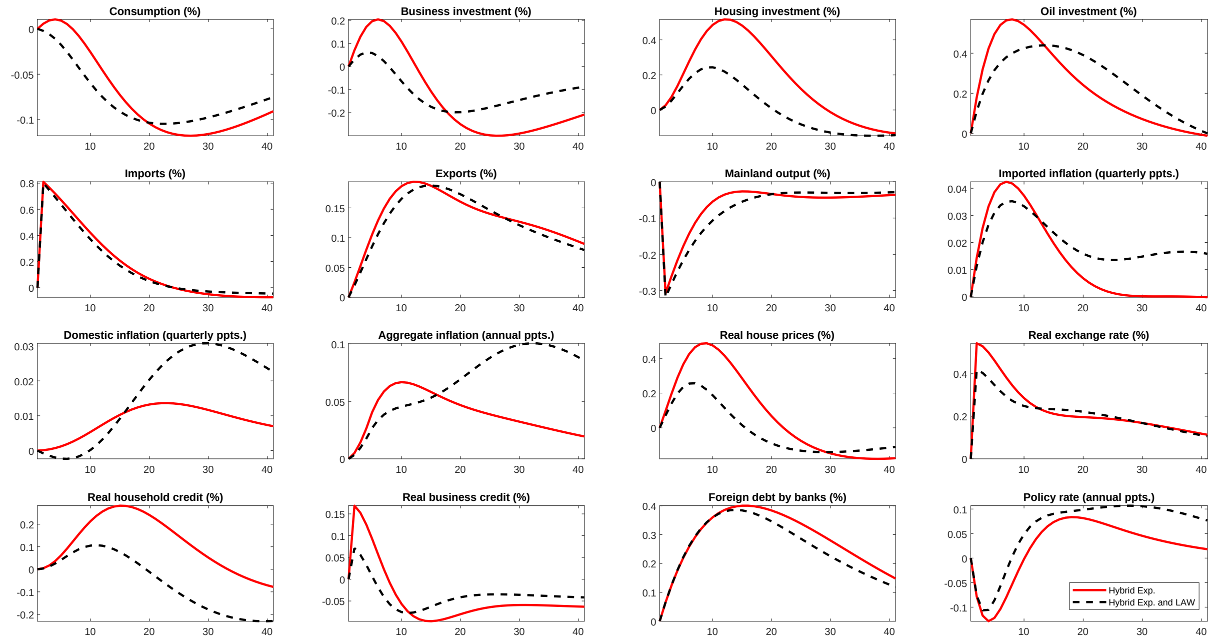

Figure 22: Impulse responses after a one SD import demand shock with and without LAW under hybrid expectations in house prices

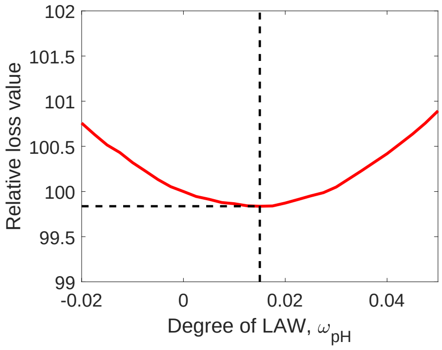

Figure 23: Relative loss values for different degrees of LAW under rational house price expectations

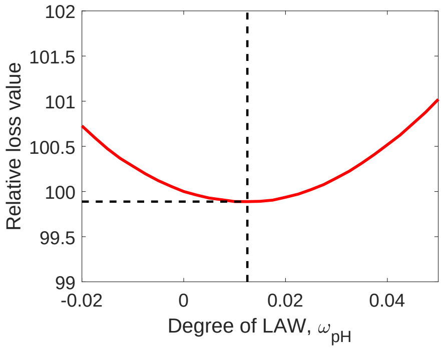

Figure 24: Relative loss values for different degrees of LAW under rational house price expectations and without crisis

Figure 23 displays the relative loss values for various degrees of LAW in the model without hybrid expectations in house prices. We obtain the lowest value when the response coefficient to real house prices is 0.015, meaning that the optimal LAW policy is to keep the policy rate 60 bp higher on average when real house prices are 10% higher on average than their long-run value. Figure 24 shows the relative loss in the model without crisis. LAW is optimal even if no crisis occurs but given the ELB and asymmetric LAW. This result is in line with studies of model economies with normal times only, such as Gambacorta and Signoretti (2014) and Cúrdia and Woodford (2016), but we can go further. The optimal degree of LAW is slightly lower if no crisis is possible compared to the case with crisis. This means that in crisis times an even higher response coefficient to house prices is optimal, and the dynamics in crisis times contribute more to the overall result under rational house price expectations.

This result is in line with the findings in other studies of LAW using systematic policy and less persistent financial cycles (see e.g. Filardo and Rungcharoenkitkul (2016) and Gerdrup et al. (2017a)).

Figure 25 shows that the expected gaps of inflation and output for higher degrees of LAW both fall but the reduction in the expected inflation gap is much lower compared to the model with hybrid expectations. Since the loss is a function of the squared mean deviations, the loss contribution from mean output increases with a higher response coefficient and the minimum loss contribution for mean inflation is around a response coefficient of 0.05. Figure 26 indicates that the volatility of inflation falls while that of output increases. This shows a trade-off between inflation and output stabilisation in the opposite direction of the previous section where inflation

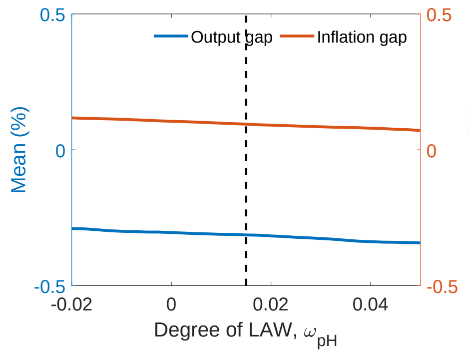

Figure 25: Expected gaps under different degrees of LAW and rational house price expectations

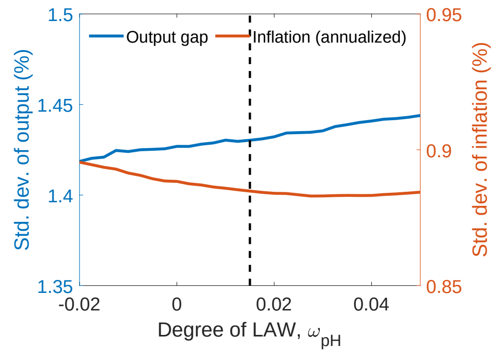

Figure 26: SDs under different degrees of LAW and rational house price expectations

volatility increases while output volatility falls under higher degrees of leaning.

This result highlights an interesting trade-off and a potential policy lesson for central banks. Trying to mitigate persistent financial cycles by implementing systematic monetary policy leads to higher inflation volatility, rendering the LAW-type policies inadvisable. When considering policy options, policymakers should consider their view on how persistent financial cycles are. Only in the case of less persistent financial cycles, would it be advisable to use systematic LAW policies.

We also conduct impulse response analyses, as in the previous section, to understand why the absence of hybrid expectations in house prices overturns the main results about optimal LAW policy. Figures 27 and 28 show the impulse responses after one SD positive wage markup and import demand shocks with and without LAW under rational expectations in house prices. The results indicate that the trade-off between inflation and output stabilisation is not as pronounced as in the model with hybrid expectations or persistent financial cycles. Especially under wage markup and import demand shocks, the volatility of inflation is not amplified to the same extent as in the previous section under the same degree of LAW. Hence, the trade-off is resolved in favour of a positive optimal LAW response coefficient.

2.5.1 Trade-off between responding to house prices vs. responding to output

The benchmark model uses the estimated mimicking rule that replicates the optimal monetary policy under discretion in normal times. When we study the optimal LAW-type monetary policy rules, we fix all other response coefficients in the mimicking rule including the output response

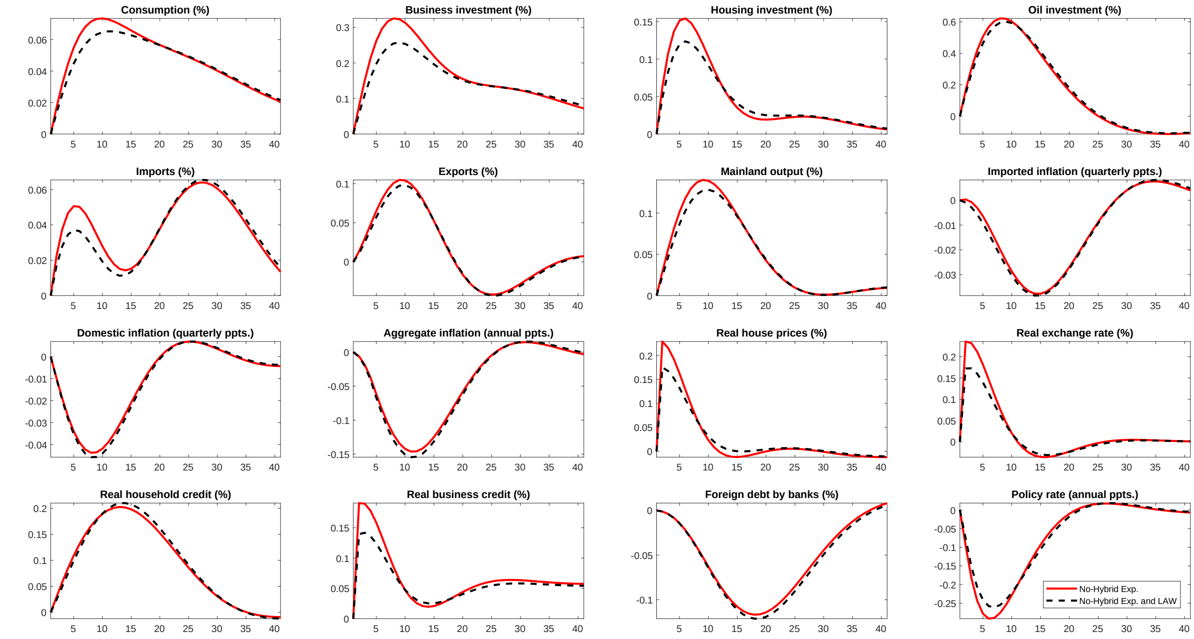

Figure 27: Impulse responses under a one SD wage markup shock with and without LAW under rational expectations in house prices

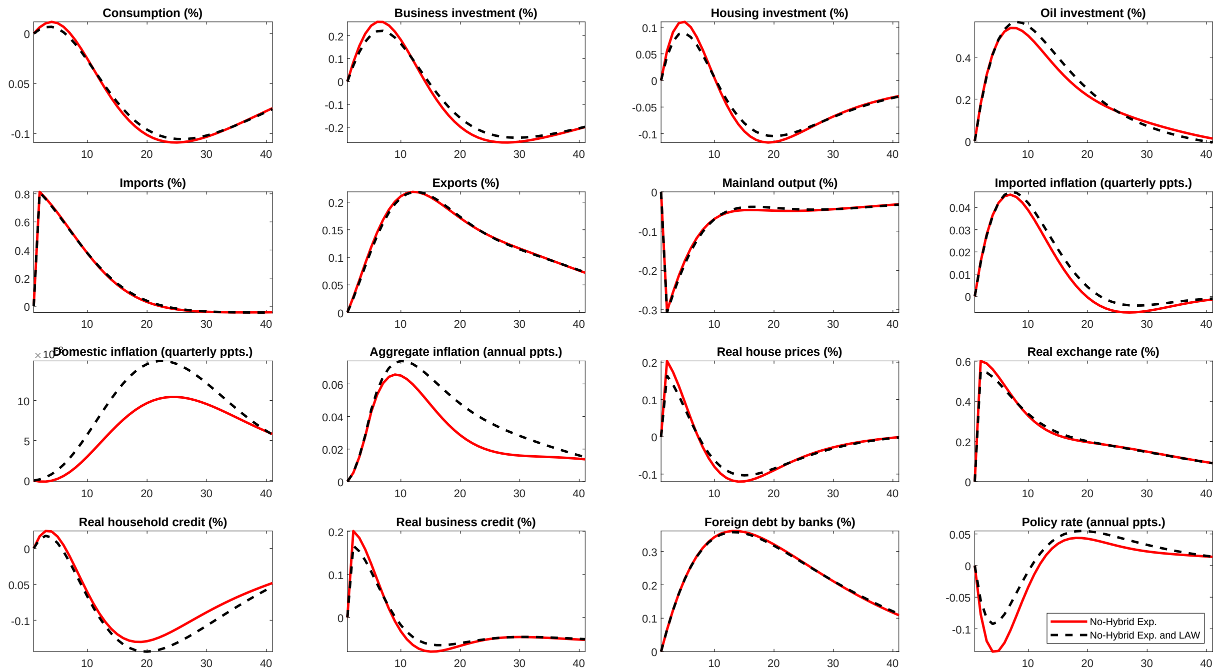

Figure 28: Impulse responses under a one SD import demand shock with and without LAW under rational expectations in house prices

at their estimated levels and only search for the optimal response to real house prices. Our main motivation is not to deviate too much from the policy rule that broadly reflects applied monetary policy. One might argue that by responding to output, the policy rule essentially responds to house prices. Therefore, when we fix the output response, obtaining a positive response to real house prices could be less likely.

Table 4: Simple correlations in the data

Variables	Mainland output	Real household credit	Real house prices
Mainland output	1	-	-
Real household credit	0.45	1	-
Real house prices	0.42	0.70	1

Notes: The data sources are Norges Bank and Statistics Norway. The sample period is from 2001Q1 to 2020Q1. Mainland output is computed as the cyclical deviation from its long-run trend. Real household credit and real house prices are computed as five-year cumulative growth rates.

Table 4 suggests that positive credit/house price developments tend to accumulate alongside higher output gaps. House prices tend to lead household credit and are contemporaneously correlated with output. This seems to support the idea that an increased weight on the output gap in monetary policy may also help stabilise credit/house price developments. To test this hypothesis, we jointly search for the optimal response coefficients to house prices and output, which minimise the central bank loss. The other response coefficients in the mimicking are held fixed at their previously estimated levels.[28]

Figure 29 displays the optimal policy frontier that shows the relationship between responding to output vs. house prices. We standardise the monetary policy responses by the SDs of output and real house price gaps in the model simulations. Any pair of policy responses on the solid red line gives the minimum central bank loss. The negative relationship clearly shows the trade-off. If the policy rule features an output response of 120 bp, which is the current output response in the mimicking rule, the optimal house price response is null. If the policy rule features a house price response of 30 bp, then the optimal output response is zero. We then explore whether the loss can be further minimised under a different combination of responses to house prices and output.

Figure 30 displays the loss values against different degrees of LAW and output responses. In the baseline model with an output response of 0.3, the loss is minimised when monetary policy does

[28] The results underline why it is important to keep all other coefficients fixed. The collinearities are prohibitive for identification of any effect by LAW.

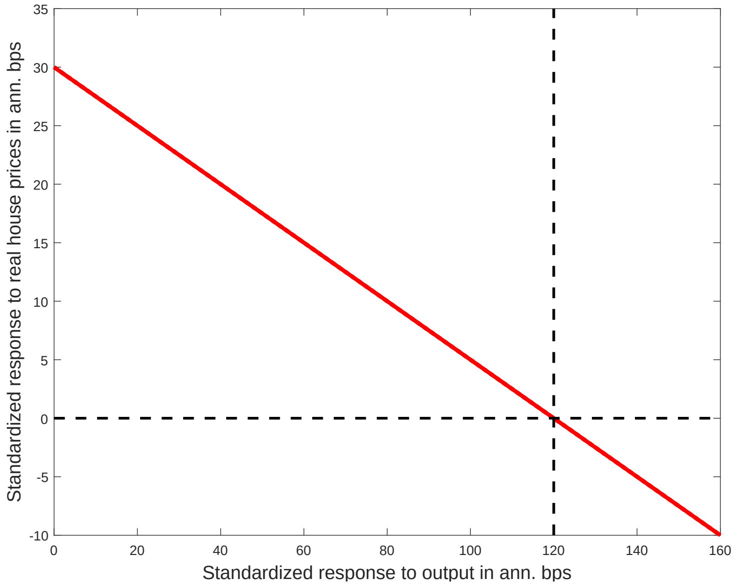

Figure 29: Trade-off between responding to house prices vs. output

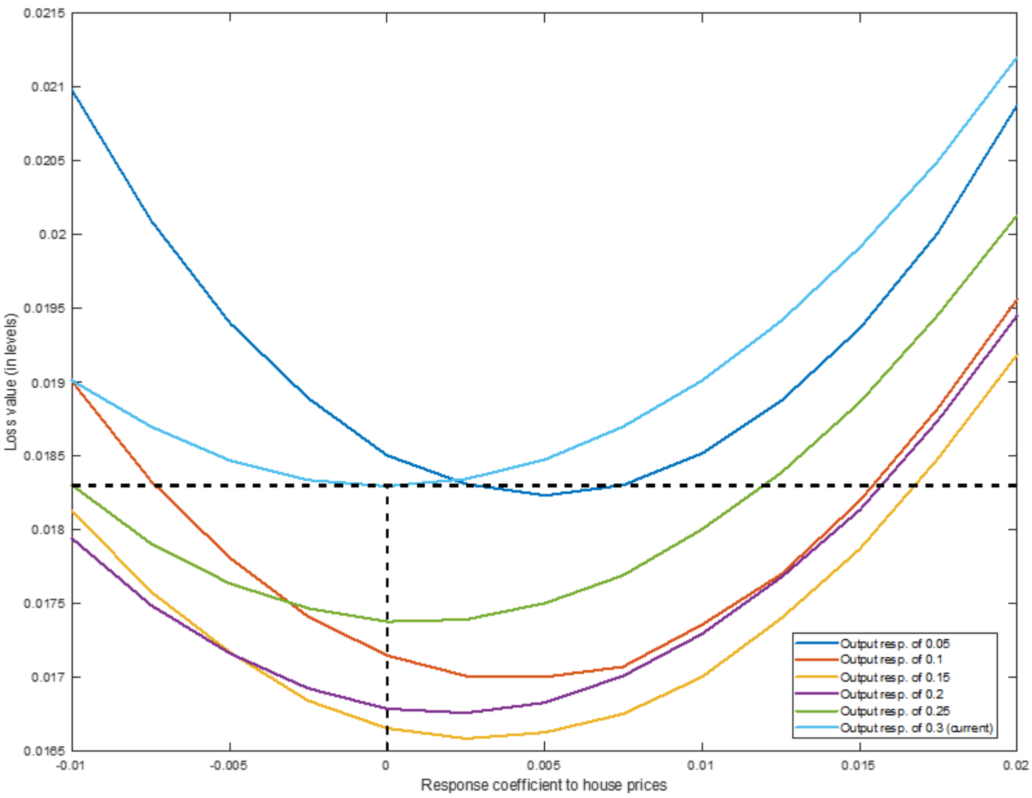

Figure 30: Loss values under different responses to output and house prices

not lean against the wind. However, a combination of a lower response to output of 0.15 than the current one of 0.3 and a positive response to house prices of 0.0025 (displayed by the yellow line) achieves an even lower loss than the baseline case. Therefore, LAW policies significantly depend on the policymaker's preference for output stabilisation.

We also conduct a battery of robustness checks in our framework in Section B examining different magnitudes of crisis probability and severity, different financial variables that monetary policy could respond to, when the ELB constraint is removed or the CCyB is not released during crises. The main results of the paper are robust to these assumptions and modifications.

2.6 LAW by macroprudential policy: Optimal long-run capital requirements

In this section, we study optimal LAW-type macroprudential policy in the form of optimal long-run bank capital regulation that minimises the central bank loss.[29] Since we aim to evaluate the effects of macroprudential policy in isolation, we use the baseline estimated mimicking rule that does not respond to real house prices. We also use the same central bank loss function that reflects the same preferences of inflation and output stabilisation as in the previous section. We do not consider an additional financial stability mandate since we would like to conduct a comparable policy experiment to the one above regarding monetary policy. To find the optimal bank capital regulation in normal times, we conduct a grid search over the different values of SS capital requirements from 11.3% to 18.2% with equally-sized grid points of 0.5%. We then investigate how long-run bank capital requirements affect the benefits and costs of LAW.

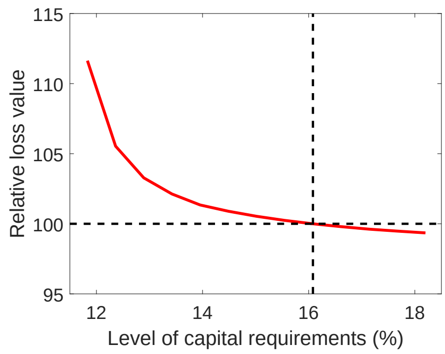

Figure 31: Relative loss values for different levels of long-run capital requirements

Figure 31 displays the relative central bank loss values with respect to the level of bank capital requirements. The results suggest that losses fall with higher bank capital requirements in normal

[29]We also investigate the optimal time-varying CCyB rules that respond to real house prices or real household credit using the same central bank loss function as in the monetary policy experiment. The rules we study fluctuate around a long-run CCyB value of 2.5%. We find that although higher degrees of LAW by using time-varying CCyB lead to lower loss values, the reduction is negligible.

times but higher capital requirements are subject to diminishing returns.

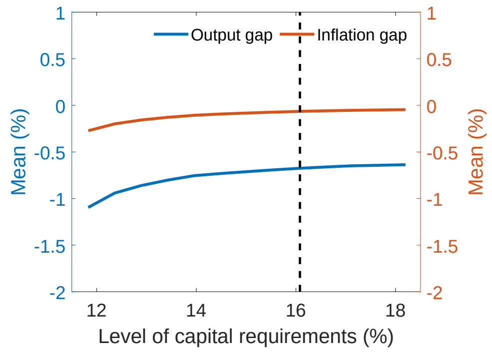

Figure 32: Expected gaps under different levels of capital requirements

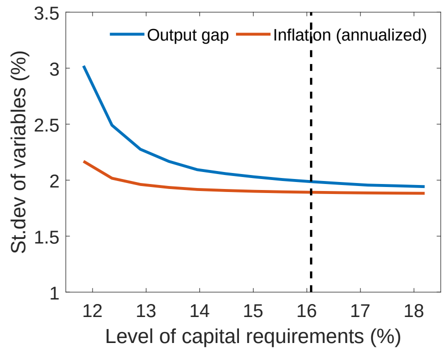

Figure 33: SDs under different levels of capital requirements

Figures 32 and 33 display the expected gaps and the SDs of inflation and output under different levels of long-run capital requirements. Both figures show that higher long-run capital requirements decrease the mean gap across regimes and bring down both inflation and output volatility.

Figure 34 shows that some of these benefits come from the fact that the economy spends less time in the crisis regime. Yet, higher SS capital regulation leads to a limited reduction in the total time spent in crisis episodes. This is consistent with Jordà et al. (2021), who find no relationship between higher bank capital and crisis risk.

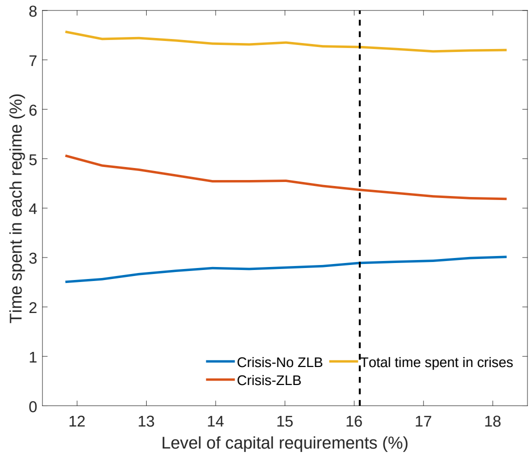

Figure 34: Time spent in crisis regime under different levels of capital requirements

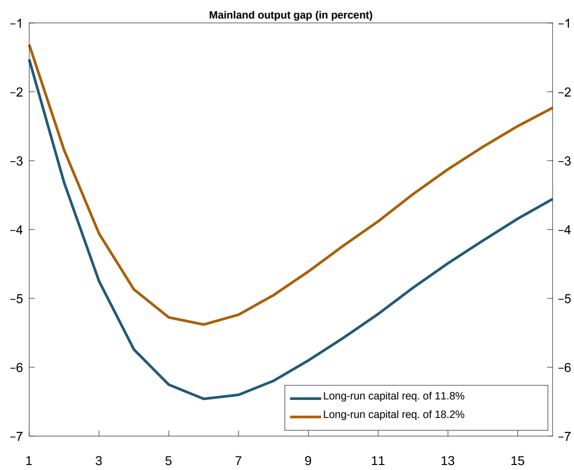

Figure 35: Dynamics of output during financial crises under different levels of capital requirements

Figure 35 displays the dynamics of output during crises when the long-run levels of capital requirements are 11.8% (solid blue line) and 18.2% (solid orange line). When the long-run capital requirements are higher, the average depth of crises is smaller and the recovery is faster. This finding is also in line with Jordà et al. (2021), who argue that recovery from financial crises is faster for countries with banking sectors that are better capitalised. This benefit is more important in magnitude than its effect on crisis probability.

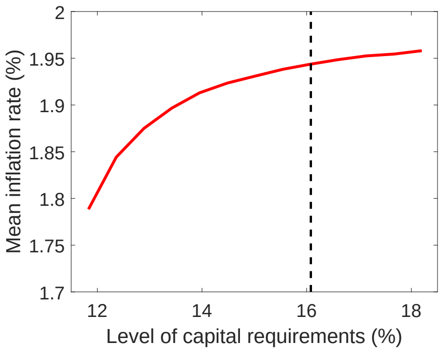

Figure 36: Mean inflation rate in normal times

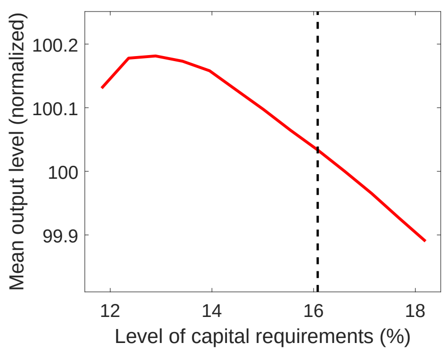

Figure 37: Mean output level in normal times

Figures 36 and 37 display the means for both the inflation rate and output level in normal times for various levels of capital requirements. Higher capital requirements increase the mean inflation rate and bring it closer to the 2% inflation target since they reduce the frequency of ELB episodes. Under higher capital requirements, the banking sector is more resilient to macroeconomic and financial shocks. Therefore, the negative shocks of the same magnitude do not lead to deflationary effects and the economy performs better. However, negative shocks reduce the mean level of output after around 13% capital requirement. After that point, the adverse effects of higher capital requirements that raise credit spreads and hence the cost of funding start to dominate the stabilising effects of capital requirements.

Figure 38 shows how much time the model economy spends in ELB episodes under different levels of capital requirements. The figure indicates that higher long-run capital requirements substantially reduce the probability of hitting the ELB by increasing the mean inflation rate, as shown in Figure 36.

The benefits of lower inflation and output volatility, higher mean inflation and output in crisis times, and lower crisis probability and severity clearly outweigh the costs of lower output in normal times. The reaction of inflation and output is markedly different compared to LAW by

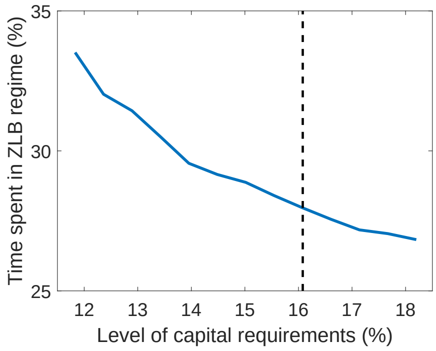

Figure 38: Time spent in ELB episodes for different levels of capital requirements

monetary policy and this begs the question of whether a combination of both policies might be optimal. This question is beyond the scope of the current paper and is left for future research.

3 Conclusion

This paper investigates to what extent monetary policy should consider financial imbalances. We focus on systematic policy in which the policymaker implements policy in a systematic way and everybody is aware of the policymaker's intention. Furthermore, we explore to what extent the persistence of financial cycles and the ELB matter in the policy evaluation. Last but not least, we evaluate different ways of implementing LAW policies, such as symmetric and asymmetric policy.

We find that a monetary policy strategy that attempts to systematically tame the persistent financial cycle leads to excessive inflation volatility because it amplifies the supply shocks and leads to a higher frequency of ELB episodes due to the lower mean inflation rate it induces. LAW is only advisable if the policymaker cares more about output stability relative to inflation stability or if financial cycles are less persistent, exclusively under systematic LAW. In this case, LAW dampens house price volatility and is countercyclical in response to supply shocks. The countercyclical effect of house prices acts through the collateral channel and manifests itself in higher inflation volatility under persistent financial cycles. Under rational house price expectations, the same collateral channel leads to a reduction in output volatility.

One can also consider or even combine the LAW policy with the "mopping after crash"-type policies that respond to house prices (or to financial variables in general) during financial crises episodes within our framework. However, we choose to confine our analysis particularly to the LAW-type monetary policy rules that implies a somewhat tighter policy rate than what is consistent with flexible inflation targeting mandates of inflation and output stabilization by assuming that monetary policy does not respond to house prices during crises. Assessing how "mopping after crash"-type policies could perform in terms of inflation and output stabilization is left for future research.

Macroprudential policy in the form of long-run bank capital requirements is a better way address risks to financial stability, and the benefits increase with higher requirements in normal times. Capital requirements lower both output and inflation volatility, and are therefore a natural complement to LAW by monetary policy. We leave the optimal combination of monetary and macroprudential policies for further research.

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Online Appendix for "Leaning against persistent financial cycles with occasional crises"-Not intended for publication

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Abstract

This online appendix includes the analyses on the effects of the ELB and CCyB on the evolution of financial crises, robustness checks for the main results of the paper, and an analysis of nonsystematic LAW. It also contains details about the underlying DSGE model. In particular, it presents the detailed mathematical derivations of the optimality conditions, explains the data sources and targeted empirical moments in the calibration of the steady-state of the model, and describes the Bayesian estimation of the baseline model in the main text.

JEL: E52, E58, G01

Keywords: leaning against the wind, monetary policy, financial cycle, macroprudential policy

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A The effects of the ELB and CCyB on the evolution of financial crises

A.1 The effects of the ELB on the dynamics of financial crises

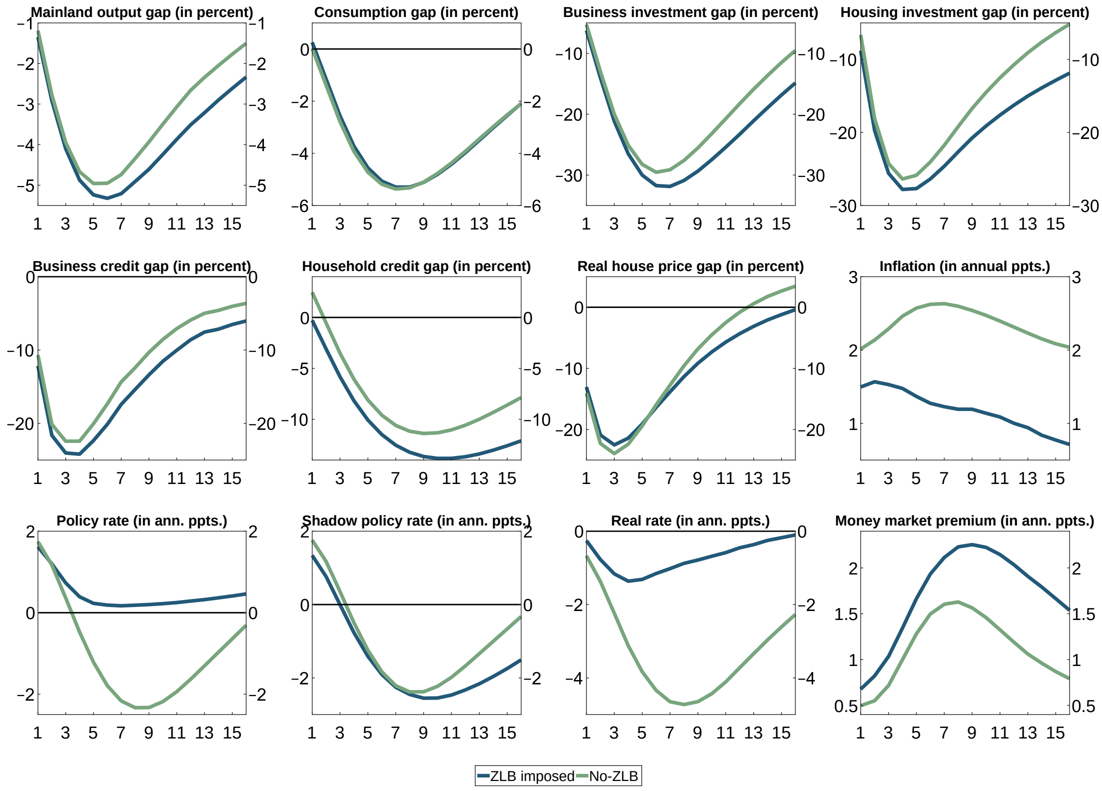

Figure 39: Main crisis scenario under ELB versus No-ELB

Figure 39 displays the average effect of imposing the ELB on the nominal policy rate on the dynamics of the main macroeconomic variables during crises. In the case of no-ELB, the policy rate could fall below -2% at its trough and the real rate could decline to about -4%. The level of the money market premium under ELB is higher compared to the no-ELB case but the difference is smaller than the one in the policy rate. As a consequence, the lending rate is higher in the case of the ELB and credit and output lower. Consumption remains virtually unchanged. The rise in the inflation rate is higher in the no-ELB regime due to both a higher SS inflation rate and a lower policy rate.

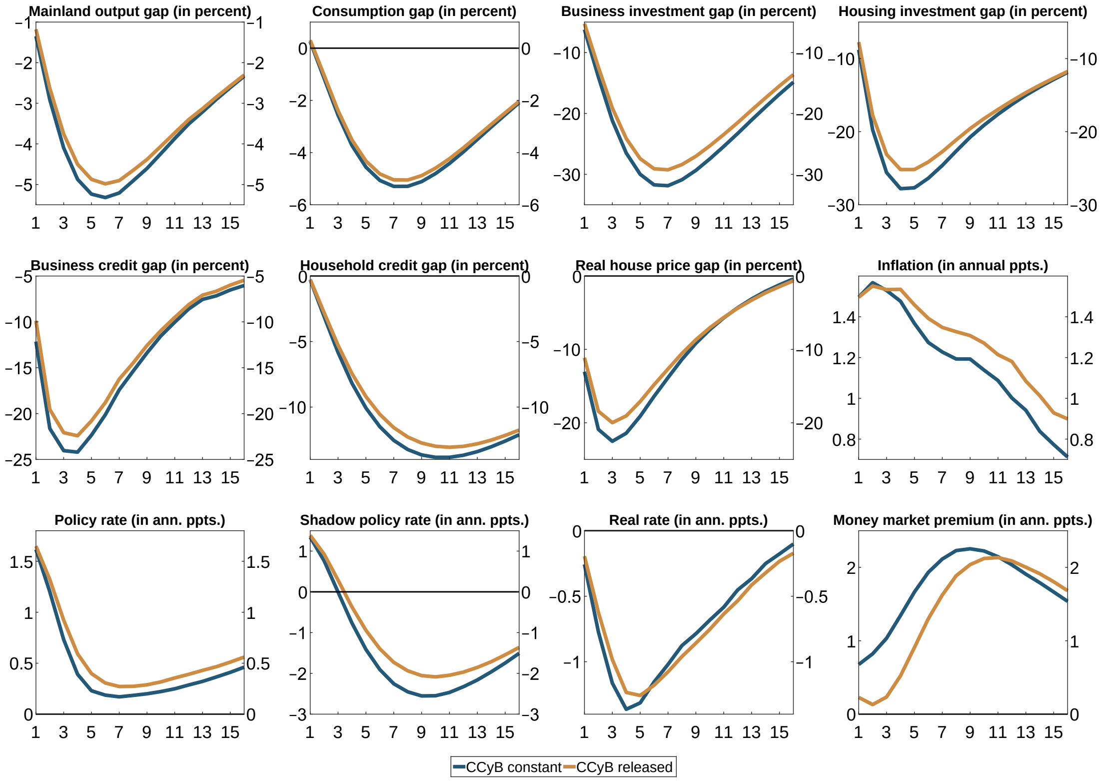

Figure 40: Main crisis scenario under a 2.5% CCyB versus a zero CCyB (ELB is imposed)

A.2 The effects of a CCyB release on the dynamics of financial crises

Figure 40 shows how the relaxation of the CCyB to zero from 2.5% during crises affects the average behaviour of main macro aggregates during crises. Since the relaxation of the CCyB lowers the pressure to generate profits in order to retain earnings and accumulate bank capital, the increase in the money market premium is lower compared with a constant CCyB. Lower funding costs for the banking sector lead to higher lending to businesses and households, reducing the fall in business and housing investment, hence the decline in output. Inflation and the policy rate are also higher under a zero CCyB. However, we note that the macroeconomic effects of relaxing the CCyB during crises are not large.

B Robustness

The analyses in the main text allowed us to evaluate systematic LAW by monetary policy with and without persistent financial cycles. To undertake these experiments in a realistic setting, we introduced a range of modelling features whose quantitative impact on the dynamics we have already demonstrated. But in this section we also want to see to what extent their presence or absence changes the results of our analysis.

In the following we will conduct robustness tests regarding the: (i) magnitude of crisis shocks; (ii) sensitivity of crisis severity to excess credit; (iii) persistence of financial crises; (iv) magnitude of crisis probability; (v) sensitivity of crisis probability to excess credit; (vi) exogenous crisis probability; (vii) use of house prices instead of household credit as the variable driving crisis probability and severity; (viii) removal of the ELB; (ix) removal of the CCyB release; (x) symmetric LAW; (xi) monetary policy reacting to household credit instead of house prices, and (xii) trade-off between house prices and output response. These robustness tests concern the case of systematic policy with persistent financial cycles.

These additional experiments will allow us to test the robustness of our results and identify the contributions of certain modelling choices.

B.1 Crisis severity

B.1.1 The magnitude of crisis shocks

To gauge the effect of a higher crisis shock, we increase the magnitude of crisis shocks such that we obtain a fall in output that doubles the decline in the benchmark model (a little more than 10%) by raising the constant term (γ) in the crisis severity function described in equation (6) from 0.3 to 0.55. In general, larger crisis shocks should make LAW more favourable because the central bank will then have more incentive to prevent an even more severe crisis.

Comparing the loss as a function of the response coefficient across the specification with a higher crisis shock (see Figure 41) and our benchmark specification (see Figure 8), we find that the point of lowest loss is the same (LAW=0) but the loss increases more strongly as soon as LAW policies are implemented. In other words, the marginal loss is larger with a higher crisis shock. This leads us to conclude that for higher crisis shocks the changed decision rules as a result of systematic policy have negative effects which just about compensate for the positive effects of implementation. Because agents understand that the central bank implements LAW-type policies, they change their behaviour such that the economy is more volatile and ultimately central bank losses are higher due to this effect in isolation.

B.1.2 The sensitivity of crisis severity to excess credit

Another way of assessing the impact of higher crisis severity is to change the sensitivity of crisis severity to excess household credit growth. To that end, we raise the slope term (γ_{B_h}) in the crisis severity function (6) from 1 to 3. The effect and logic should be the same as for the previous robustness test.

We come to the same conclusion here as for the previous robustness test. The optimal degree of LAW is 0 and the marginal effect only from the implementation is positive, meaning that the changed decision rules have a negative impact that offsets the other effect. Figure 42 shows that higher degrees of LAW still increase the central bank loss values even under higher crisis severity.

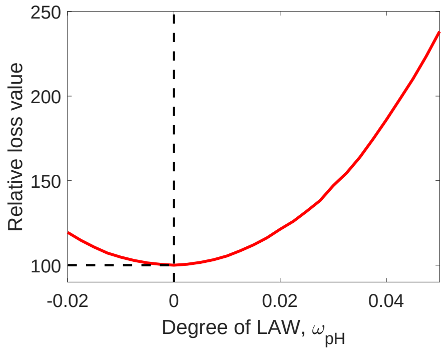

Figure 41: Relative loss values for different degrees of LAW under higher crises severity

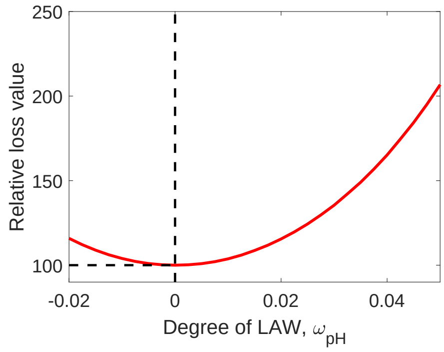

Figure 42: Relative loss values for different degrees of LAW under higher sensitivity of crisis severity to excess credit

B.1.3 The persistence of financial crises

The persistence of financial crises is a key parameter in the costs-benefit analysis of LAW. The cost of a crisis increases substantially the longer it lasts, which makes LAW-type policies more favourable. In order to test it, we increase the persistence of the crisis shocks (ρ_{crisis}) from 0.7 to 0.95. We also recalibrate the probability (constant term in the logit function as -4.395) and the severity of crises ($\gamma = 0.1$, and $\gamma_{B_h} = 0.47$) such that we obtain the same maximum decline in output during crises. Figure 43 indicates that a higher response to real house prices still leads to an increase in loss values even under more persistent financial crises.

B.2 Crisis probability function

B.2.1 The magnitude of crisis probability

We increase the constant term in the probability of crisis function from -4.25 to -3.25 to obtain an annual probability of a crisis start of 6% in the long run. Giving more importance to the crisis regime, any measures preventing or mitigating the crisis should be more important. The results show that they do not change the conclusion from the benchmark case (see Figure 44).

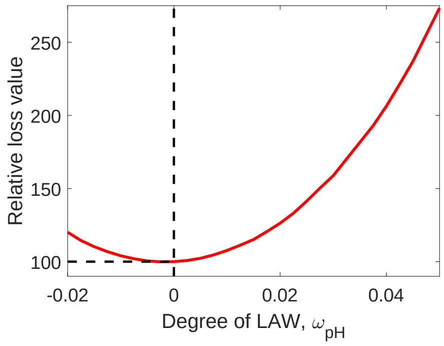

Figure 43: Relative loss values for different degrees of LAW under more persistent financial crises

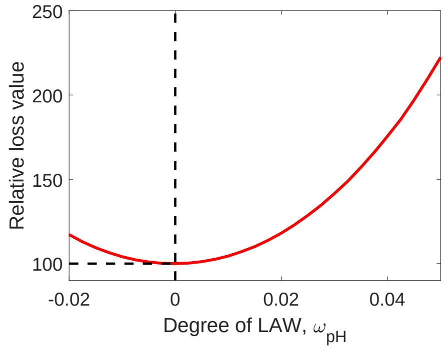

Figure 44: Relative loss values for different degrees of LAW under higher crisis probability

B.2.2 The sensitivity of crisis probability to excess credit

We increase the slope term in the probability of crisis function from 0.0223 to 0.0523. Thus, the sensitivity of crisis probability to excess household credit is more than doubled, and again LAW should be more effective given the larger effect on crisis probability. This might increase the policymaker's incentive to curb excess credit more using LAW policies to prevent crises from happening. Figure 45 shows that our main result remains robust to this alternative specification of the crisis probability function. Higher degrees of LAW still raise the central bank loss values, and the higher inflation volatility is the root cause of higher losses.

B.2.3 Exogenous crisis probability

We also investigate whether the fact that the probability of crises endogenously depends on excess household credit growth has any effect on the optimality of LAW policies. This might reduce the policymaker's willingness to mitigate excess credit growth and to deploy LAW policies. In effect, this only leaves the effect on the economy in normal times and crisis severity. Since most of the time is spent in the normal regime, it is not surprising that the results do not change and it is not advisable to respond to house prices (see Figure 46).

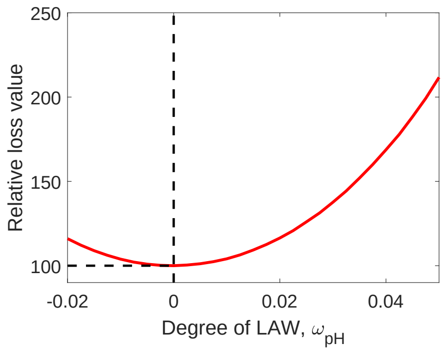

Figure 45: Relative loss values for different degrees of LAW under higher sensitivity of crisis probability to excess credit

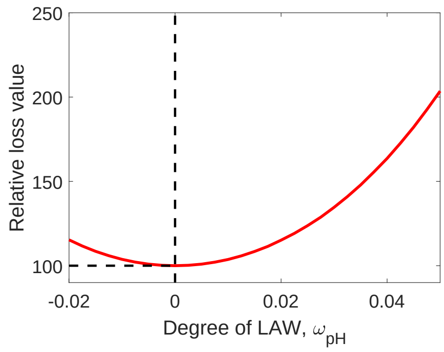

Figure 46: Relative loss values for different degrees of LAW under exogenous crisis probability

B.3 Five-year cumulative house price growth in crisis severity and probability

We use five-year cumulative real household credit growth in both the probability and the severity of crises in our main analyses of systematic policy. One may question the plausibility of this assumption and ask whether the main findings change were we to use an alternative indicator of financial imbalances in crisis probability and severity such as five-year cumulative real house price growth. Such price growth is also shown to be an important indicator of financial vulnerabilities in the literature. We rely on the estimate in Table 5 and find that LAW is not advisable even if we use house prices instead of household credit (see Figure 47).

B.4 No ELB on policy rate

Our benchmark model of systematic policy incorporates an endogenous ELB on the policy rate, which limits the ability of monetary policy to counteract large negative macroeconomic shocks and hence to maintain inflation and output stabilisation. This feature impacts LAW because higher degrees of LAW reduce the mean inflation rate, in turn leading to a lower average policy rate and to an increased probability of hitting the ELB. Then again, Table 3 shows that inflation volatility increases without the ELB, and output volatility decreases slightly. Removing the ELB as a constraint on monetary policy may lower the costs of LAW, yet the results show that it does not change the main result (see Figure 48). In other words, the ELB is not the driving factor behind the results.

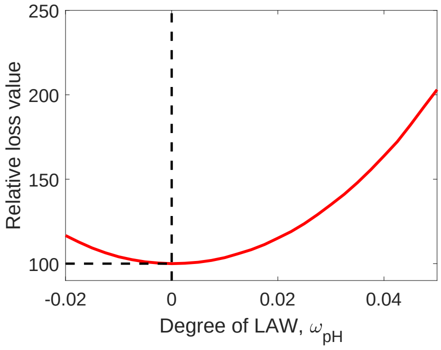

Figure 47: Relative loss values for different degrees of LAW when house price growth is in the probability and severity of crises

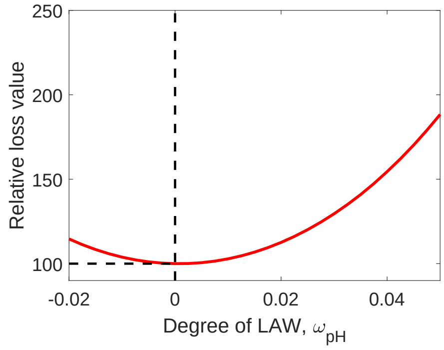

Figure 48: Relative loss values for different degrees of LAW under no ELB constraint

B.5 No CCyB release during crises

In the benchmark model, we assume that the CCyB is released from its long-run value of 2.5% to 0% during financial crises. The release gives banks relief in crisis times and reduces crisis severity. Removing the release will magnify crisis severity slightly as we have seen the effect of the CCyB to be small (see Figure 40). We suspect that the more severe crisis tilts the balance in favour of LAW but, as we have already seen previously, changes in crisis severity did not change the main result. Figure 49 indicates that our main finding remains unchanged under this alternative assumption.

B.6 Monetary policy response

B.6.1 Symmetric LAW

We consider asymmetric LAW policies in the benchmark systematic policy model since we think it is more reasonable to assume that the central bank responds to the real house price gap or household credit growth when they are positive. One may argue that the central bank may want to reap the benefits of stable house prices or household credit growth in normal times by also responding to these variables when they fall. The monetary authority can reduce the policy rate in response to a decline in house prices in normal times to stabilise the housing market. This can potentially contribute to a better performance of the economy in normal times by reducing the fluctuations in inflation and output. Figures 49 and 50 suggest that the symmetry of LAW does not change the main result and it is not an assumption which drives the results.

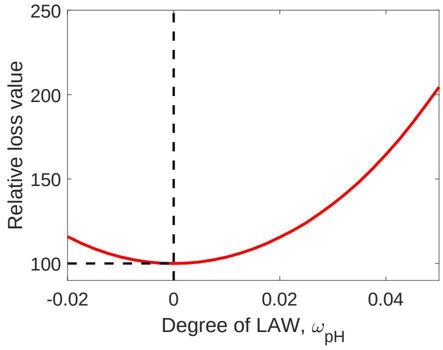

Figure 49: Relative loss values for different degrees of LAW when CCyB is not released during crises

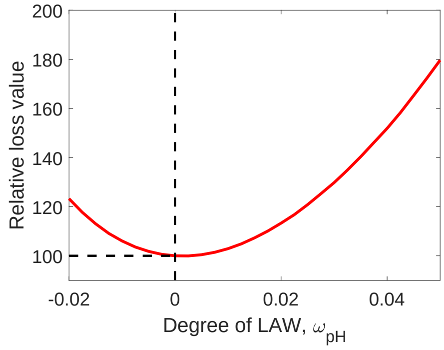

Figure 50: Relative loss values for different degrees of LAW under symmetric LAW

B.6.2 Response to real household credit gap

In this section, we consider an alternative financial variable that monetary policy can respond to – the real household credit gap instead of real house prices. Although monetary policy is considered to be less effective in mitigating household credit due to its substantial inertia, the central bank may want to respond directly to household credit since it is the main source of friction in the economy, i.e. both the probability and the severity of crises are functions of household credit.

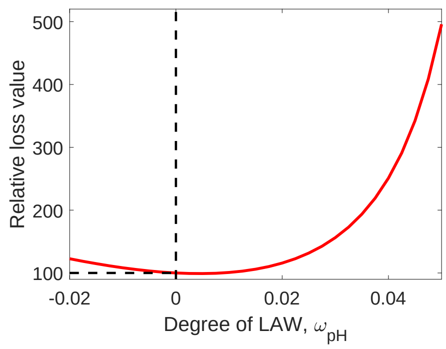

Figure 51: Relative loss values for different degrees of LAW when monetary policy responds to the real household credit gap

In fact, the optimal response coefficient is not zero when responding to household credit instead of house prices. LAW is optimal with a small coefficient of 0.005 (see Figure 51). Responding to the variable that we assume to directly influence crisis probability and severity proves to be beneficial. Monetary policy is less effective in influencing the highly persistent financial cycle (in the form of stocks of debt), whereas house prices are more elastic with respect to changes in monetary policy and thereby more practical to target.

C Non-systematic LAW policy

The analysis of non-systematic LAW in this paper goes further than Svensson (2017a) and Kockerols and Kok (2021) along two lines. First, we explicitly differentiate between non-systematic LAW policy, where the policymaker implements the policy as a one-off surprise, and systematic policy, where LAW is implemented in a rule-based way so that economic agents fully incorporate central bank's intentions. This distinction is important because by being built into forward-looking expectations, systematic policy can be deemed more useful than non-systematic policy as a stabilisation tool especially when aggregate demand depends on contemporaneous asset prices, which are forward looking. Second, we analyse whether the results of the previous studies hold in a model with persistent house prices and credit.

The framework for non-systematic LAW is generally inspired by Svensson (2017a) but differs from it in two key dimensions. The Svensson (2017a) environment is a stylised Markov switching setup where the economy is represented by the dynamics of a DSGE model in normal times and an additional constant shock in crisis times. In contrast, our underlying model incorporates persistent financial cycles via hybrid house price expectations. Furthermore, we let the monetary policy intervention coincide with a shock, which widens financial imbalances, leading to an imminent crisis. Last but not least, we determine the optimal size and direction of the policy interventions evaluated over a decade.

We find that non-systematic LAW is not advisable under persistent financial cycles because the benefits of less frequent and milder crises emerge smaller than the costs of depressing the economy with higher interest rates. Particularly, non-systematic LAW reduces both volatility and the ergodic mean levels of inflation and output. Consequently, our results show that for non-systematic policy, leaning with the wind is optimal. This finding also holds under rational house price expectations (and hence less persistent financial cycles), even though welfare costs from non-systematic LAW decline in this case. The increase in welfare losses from non-systematic LAW under persistent financial cycles hinges on the fact that monetary policy shocks have a stronger negative impact on inflation relative to output. Thus, higher persistence in house prices and household debt makes non-systematic policy generate larger costs, rendering it not optimal.

Therefore, for the non-systematic LAW, we add to the insights provided by Svensson (2017a), by uncovering a novel result that empirically relevant, persistent financial cycles further increase the costs of non-systematic LAW.

C.1 Framework

The non-systematic LAW framework is inspired by Svensson (2017a) and is based on the assumption that a crisis can occur but agents in the economy including the policymaker do not foresee it. Furthermore, any policy action beyond the mandate of the policymaker in response to the possibility of a crisis is a surprise for economic agents, including the policymaker.[1] This policy, which we interpret as non-systematic LAW, is evaluated using a quadratic loss function. LAW by monetary policy, for example, means setting the interest rate higher than implied by the central bank mandate, which in turn imposes costs in terms of depressing the economy in normal times and going into the crisis. The benefits of LAW are lower crisis probability and severity. The crisis can occur at any point in time in the future, is modelled as a constant recessionary shift in the economy, and lasts for a predetermined amount of time.[2]

The loss function used to evaluate LAW policies is:

$$L_t = \min_{\mathfrak{p}_1^i} \left[(\hat{\pi}_t)^2 + \lambda_Y (\hat{Y}_t)^2 \right],$$

with, $\hat{\pi}_t$, being the inflation deviation from SS, $\hat{Y}_t$ being the output deviation from SS, and λ_Y being the weight on output. The policymaker chooses policy, $\mathfrak{p}_1^i$, to minimise the loss, L_t.

Introducing the crisis regime, we consider that when the economy is in a crisis state with probability p_t, it has inflation and output deviations, denoted by $\hat{\pi}_t^c$ and $\hat{Y}_t^c$, respectively. The probability of a crisis depends on the financial imbalances in the economy. More specifically, if 5-year credit growth is high, the occurrence of a crisis is more likely. The normal state of the economy has probability $1-p_t$, and it has inflation and output deviations $\hat{\pi}_t^n$ and $\hat{Y}_t^n$, respectively. The trajectory of the economy in normal times is fully described by the response of the economy to the policy shock in our DSGE model. Furthermore, we also consider the possibility that policy

[1] We model policy as an exogenous, unanticipated shock.

[2] Although the average duration of a typical crisis episode is calibrated to be eight quarters to be consistent with the most empirical evidence, its impact lasts longer due to the scarring effects of financial crises on output documented in the literature.

is implemented when the economy is not in SS but away from it due to a shock driving-up of financial imbalances (house prices and credit). Thus, policies will be assessed when they are supposedly the most effective.

We can then rewrite the loss as a function of both regimes:

$$L_t = \min_{\mathfrak{p}_1^i} \left[(1-p_t) \left((\hat{\pi}_t^n)^2 + \lambda_Y (\hat{Y}_t^n)^2 \right) + p_t \left((\hat{\pi}_t^c)^2 + \lambda_Y (\hat{Y}_t^c)^2 \right) \right].$$

The crisis inflation and output deviation, $\hat{\pi}_t^c$ and $\hat{Y}_t^c$, is composed of a crisis increase in the inflation rate, Δ_t^π, a reduction in output, Δ_t^Y, net of any policy reaction during the crisis ,and the non-crisis deviations, $\hat{\pi}_t^n$ and $\hat{Y}_t^n$. The crisis shifts depend on the financial imbalances as well. If pre-crisis credit growth is high, the crisis is going to be more severe.

Another way of writing the loss function using the previously defined variables is then:

$$L_t = \min_{\mathfrak{p}_1^i} \left[(1-p_t) \left((\hat{\pi}_t^n)^2 + \lambda_Y (\hat{Y}_t^n)^2 \right) + p_t \left((\Delta_t^\pi + \hat{\pi}_t^n)^2 + \lambda_Y (\Delta_t^Y + \hat{Y}_t^n)^2 \right) \right].$$

In order to evaluate policy, we calculate and compare the loss for different policies $\mathfrak{p}_1^i$ over 40 quarters. Furthermore, we decompose the loss into the policy effect on the mean and SD of inflation and output:

$$L_t = \min_{\mathfrak{p}_1^i} \left[(\mathbb{E}_t[\hat{\pi}_t])^2 + \lambda_Y (\mathbb{E}_t[\hat{Y}_t])^2 + \text{var}(\hat{\pi}_t) + \lambda_Y \text{var}(\hat{Y}_t) \right]. \quad (11)$$

C.2 Calibration

The probability of being in a crisis is determined, assuming a Markov process, by the probability of a crisis start and the crisis duration. We assume the crisis duration to be eight quarters, which reflects the mean unfiltered peak to trough duration of the financial cycle in Europe as defined in Schüler et al. (2015).[3]

Schularick and Taylor (2012), Jordà et al. (2013), and Mian and Taylor (2021) argue that credit developments increase both the probability and severity of crises. We also rely on five-year credit growth as a proxy for both the probability and severity of a crisis, and this choice is

[3]The crisis duration of eight quarters is to be seen in combination with the 5 pp reduction in output. Taken together, 10 pp-years of output deviation determine the severity of the crisis in the model.

empirically supported by Arbatli-Saxegaard et al. (2020), who find that five-year credit growth has the most significant effect on downside risks to output growth in Norway. Underlying the quarterly probability of a crisis start is a logistic function that links the policy impact via five-year cumulative growth in real household credit to the probability of a crisis start.[4] We use an estimated logistic regression for the (quarterly) probability of a crisis start, q_t: $q_t = 1 - \frac{1}{1+\exp(4.792-2.232D_t^{\Delta 5Y})}$, on five-year cumulative growth in real household credit, $D_t^{\Delta 5Y}$, based on a sample of twenty OECD countries over the period 1975Q1 - 2014Q2 (Gerdrup et al., 2017a). We also conduct a robustness check by using an estimated crisis start probability function that depends on five-year cumulative growth in real house prices. The estimated parameter values are given in Table 5.

Table 5: Estimated parameters in the logit model

	Probability of crisis start	
Five-year cum. growth in real household credit	2.232**	
	(1.099)	
Five-year cum. growth in real house prices		1.896***
		(0.607)
Constant	-4.792***	-4.804***
	(1.026)	(1.005)
Country fixed effects	Yes	Yes
Pseudo R-Squared	0.0424	0.0348
AUROC	0.666	0.688
Observations	1832	2070

Notes: Significance levels: *10%, **5%, ***1%.

Figure 52 plots the annualised crisis start probabilities as a function of either real household credit growth or real house price growth. The probability of a crisis start increases from 3.3% to 4.85% when five-year cumulative real household credit growth is one standard-deviation (17%) higher.[5]

Using a simple linear approximation[6], these values imply an SS probability of being in a crisis of around $p_t = 6\%$. The quarterly probability of a crisis start is used in both parts of the analysis as outlined above.

As for the constant crisis shifts as a function of financial imbalances, we assume the following

[4]See Ajello et al. (2019) and Gerdrup et al. (2017a) for other examples where they use household credit growth as a proxy for crisis severity and probability.

[5]Svensson (2017a) estimated an annualised probability of a crisis start of 3.2% based on a linking function using a database of 14 developed countries for 1870-2008 (Schularick and Taylor, 2012).

[6]The linear approximation is the sum of the quarterly probabilities of a crisis start over eight quarters: $p_t \approx \sum_{i=0}^{n-1} q_{t-i}$.

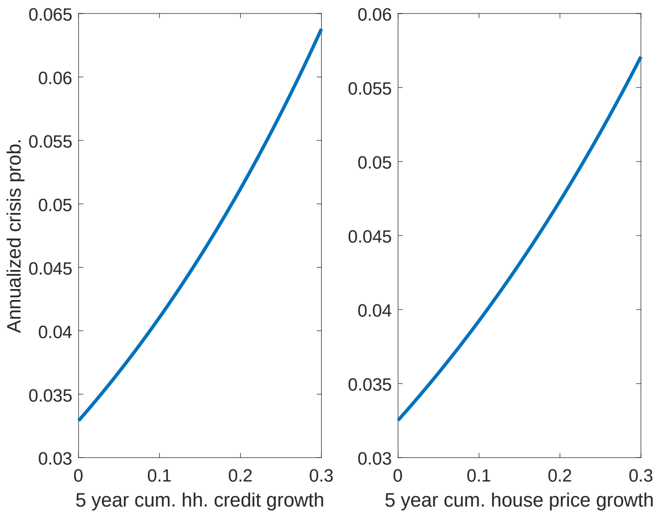

Figure 52: Crisis probability function

functional forms:

$$\Delta_t^Y = -3.82 - 0.059 D_t^{\Delta 5Y}$$
$$\Delta_t^\pi = -0.82 + 0.006 D_t^{\Delta 5Y}.$$

This assumption relies on an approximation of the calibration of crisis episodes using the RS DSGE model laid out in the next section. We calibrate the average severity of crises based on the Norwegian banking crisis in the early 1990s and rely on estimates from Gerdrup et al. (2017a) and Jordà et al. (2013) to calibrate the sensitivity with respect to credit growth. This implies that output declines by 3.82 pps and inflation falls by 0.82 pps in an average crisis in the model.

The loss function weight on output, λ_Y, is 0.3 and in line with the literature on optimal monetary policy.

The relevant impulse responses from the DSGE model going into the framework are real gross domestic product (GDP) and inflation deviation [pp] for the path in normal times, and real household debt growth [%] for the probability and severity of a crisis.

Last but not least, the baseline scenario without policy is that a shock increases financial imbalances (house prices and credit). The dynamics of the economy following a shock to housing preferences can be seen in Figure 53. House prices increase, giving households more collateral and thus allowing them to take out more debt and triggering a slight boom while inflation is barely impacted.

C.3 Non-systematic LAW under hybrid house price expectations

We find the optimal degree of LAW by monetary policy by minimising the central bank loss. We define LAW as the policymaker holding the policy rate at a constant higher level than the otherwise model-implied optimal policy rate (in the case of the single regime DSGE model without the possibility of a crisis) for four quarters. If there is no other shock present, Figure 54 shows the trajectory of the economy for a positive degree of LAW.

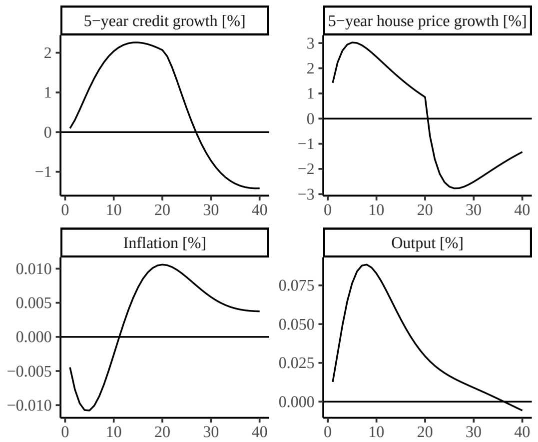

Figure 53: SS deviations for a shock to housing preferences

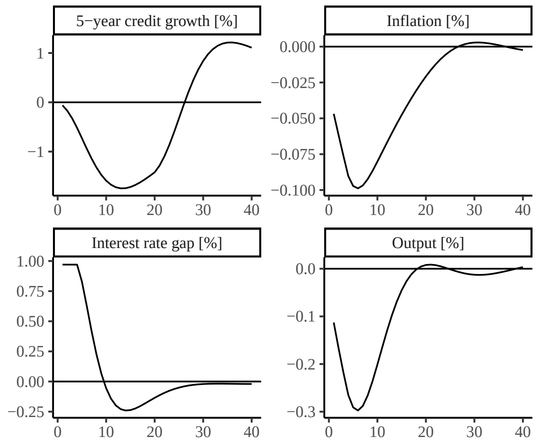

Figure 54: SS deviations for monetary policy - 1 pp increase for 4 quarters

The policymaker holds the policy rate 1 pp above the SS level for 4 quarters, which depresses output, inflation, and credit growth simultaneously.[7] The reduction in credit growth is beneficial due to the implied lower crisis probability (see Figure 55) and severity. Yet, the reduced output and inflation is a cost to the economy independent of the crisis occurring or not.

Figure 56 shows the cumulated loss over 40 quarters with varying degrees of LAW by monetary policy coinciding with a shock to housing preferences that generate a credit and house price boom. The lowest loss and thereby the optimal degree of LAW is for the policymaker to reduce the policy rate by about 0.5 pps for 4 quarters. In other words, if the policymaker acts at the same time that a shock stimulates house prices and drives credit growth, he should lean with the

[7] We construct Figure 54 by computing the trajectories of inflation, output and 5-year credit growth in response to monetary policy shocks that are extracted to obtain a conditional forecast of the policy rate being fixed for the first four quarters followed by endogenous monetary policy rule.

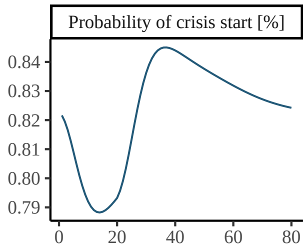

Figure 55: Probability of a crisis start over 80 quarters for **monetary policy -** 1 pp increase for **4 quarters**

wind and further support the economy instead of leaning against the wind. On the one hand, leaning with the wind means the economy benefits from the additional stimulus in normal times and also going into the crisis. On the other hand, it means that asset prices are further inflated, credit growth is even stronger and the probability and severity of a crisis are even higher. Taking both effects together, this appears to be the optimal strategy.

We can conduct the same exercise without the coinciding shock driving up house prices. This scenario would represent an unmotivated "naive" policy action. Figure 57 shows that the optimal degree of LAW is even more negative in this case. In other words, if there is no buildup of financial imbalances to lean against, then it is even less advisable to do so.

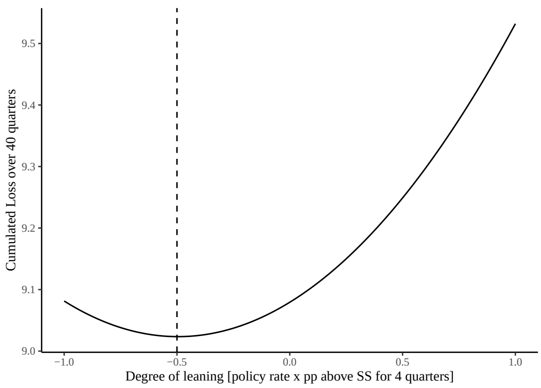

Figure 56: Loss and degree of LAW for coinciding shock to housing preferences

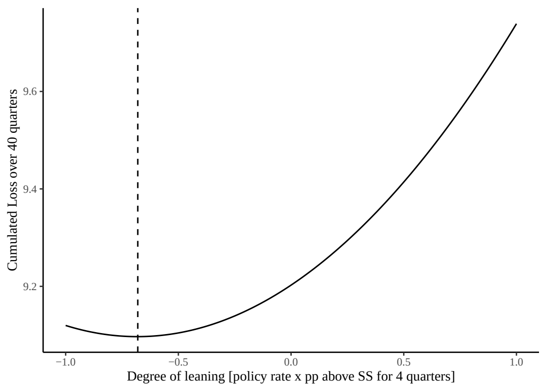

Figure 57: Loss and degree of LAW in SS

Figures 58 and 59 show the loss decomposed into the means and SD's of inflation and output (see Equation (11)) for the case of LAW coinciding with higher credit and house prices. Figure 58 shows that the higher the degree of LAW, the lower the mean output level and the mean inflation rate are. In particular, the impact on the mean output level increases the loss substantially. Figure 59 shows that the SD of inflation is lowest when there is no leaning either way, while for output the lowest SD is for a positive degree of LAW. Combined with the fact that the weight on inflation in the loss function is nearly three times as much as the weight on output, we can conclude that the loss due to the depressed mean of output contributes the most to the cost of LAW.

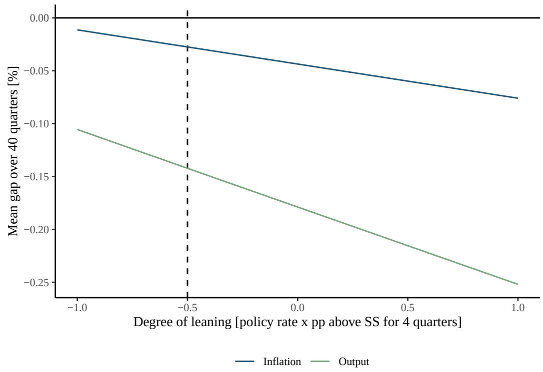

Figure 58: Mean gaps under different degrees of LAW

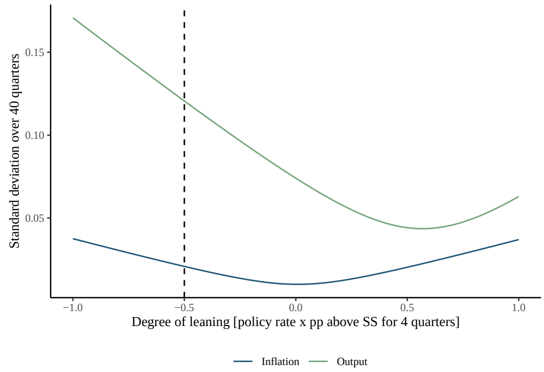

Figure 59: SDs under different degrees of LAW

C.4 Non-systematic LAW under rational house price expectations

The optimal degree of LAW under rational expectations can be found in Figure 61. Also in this case, LAW is not advisable. However, compared to the case of hybrid expectations, the degree of leaning with the wind is lower. LAW has a weaker impact on the economy and on debt levels compared to the case with hybrid expectations.

Figure 60 shows that under rational expectations, 5-year credit growth is less persistent and reacts much less to the the same 1 pp increase in the policy rate for four quarters. In other words, the variable linked to the benefits of LAW does not move as much while the costs in terms of output and inflation are about the same.

These findings are in line with the findings in Svensson (2017a), which also uses a DSGE model without persistent financial cycles. Another way to capture the effects of persistent financial cycles is to use a linking function based on early-warning models for the probability of a crisis start that captures the gradual building up of imbalances (Kockerols and Kok, 2021). Nonetheless, this approach with a calibration for the euro area also reaches the conclusion that LAW is not beneficial.

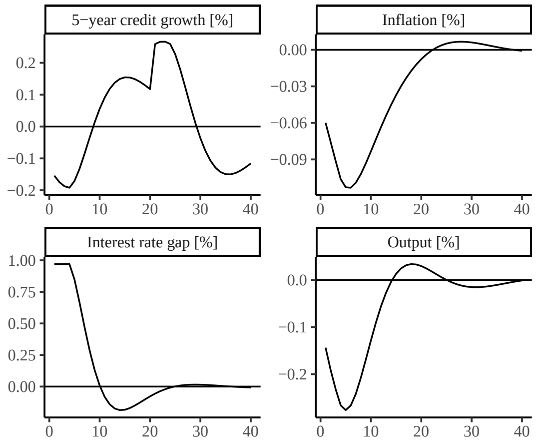

Figure 60: SS deviations for monetary policy without hybrid expectations - 1 pp increase for 4 quarters

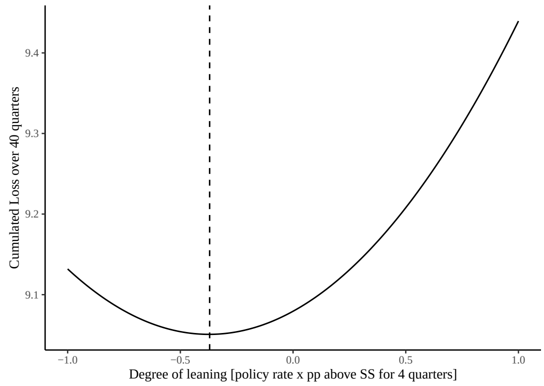

Figure 61: Loss and degree of LAW for monetary policy without hybrid expectations and a coinciding shock to housing preferences

C.5 Comparison with systematic LAW

While the calibration is similar between the approaches for the probability of a crisis, the paths for the severity of a crisis differ. In the case of non-systematic LAW, the economy is expected to contract by about 10%, which is about the same maximum decline in output obtained in the model with systematic policy. The less severe crisis in the case of systematic policy diminishes the attractiveness of LAW policies because the benefits of LAW that will be reaped in the case of a crisis are not as large given the convex loss function.

Under systematic LAW, policy adheres to an OSR, we consider the possibility of the ELB and thereby make the effectiveness of LAW state-dependent. Furthermore, the asymmetric policy rule under systematic LAW is an important component, which is impossible to capture in the non-systematic LAW framework. Last but not least, the trade-offs between inflation and output stabilisation can only be fully incorporated in the systematic LAW analysis.

Given the results outlines above and the results for systematic LAW we can conjecture that the change in decision rules due to the fact that crisis and the ELB can occur tilts the balance from LAW not being advisable back to a neutral position. In either of the two cases, any positive degree of LAW is not advisable. Furthermore, these results allow us to conclude that the changed decision rules under less persistent financial cycles tilt the balance more in favour of LAW.

D Theoretical framework: NEMO

NEMO is a large-scale DSGE open-economy New Keynesian model and is the core model used by Norges Bank for monetary policy and forecasting. The model was launched in 2006 and has been updated and extended continuously.

In this section, we summarise the main features of the constant-parameter version of the model. We give a short overview of the model's structure, go through the calibration of the steady state and the estimation of dynamic parameters, as well as show model moments and compare them to their empirical counterparts. Lastly, we discuss how monetary policy is conducted in NEMO.

D.1 Syntax and notation

Throughout this section, P_t^X denotes the nominal price of real variable X in period t. The final good is the numeraire and has the price P_t. $W_{X,t}$ is the nominal wage rate in sector X. Moreover, $R_t^X \equiv 1 + r_t^X$ is the gross interest rate associated with sector or variable X, where r_t^X is the net interest rate. All other variables are expressed in real terms unless otherwise stated.

Exogenous labour augmenting technological growth in the intermediate sector makes the economy grow at rate π_t^z. The housing sector is assumed to have a weaker technology growth rate of π_t^z/π_t^h to reflect increasing house prices relative to consumer prices observed in data. The stationary version of the model is available in Kravik et al. (n.d.). We use the notation X_{ss} to indicate variable X in steady state.

D.2 Households

Each household supplies a differentiated labour input to the intermediate goods-producing firms and the oil supply sector. Wages are set by households under the assumption of monopolistic competition. Households obtain utility from consumption, leisure, housing services and deposits. Direct utility from deposits ensures that households are both gross lenders and gross borrowers. Preferences are additively separable. We have also separated the household's problem into two maximisation problems: that of the households and that of the entrepreneurs. We do this to simplify the maximisation problem and to clarify the decision-making by the households in the model. The entrepreneurs' part of the problem is covered in Section D.5.

D.2.1 The household maximization problem

Lifetime expected utility of household j at time s is represented as

$$U_s(j) = E_s \sum_{t=s}^{\infty} \beta^{t-s} \left[u(C_t(j)) + d(D_t(j)) + w(H_t(j)) - v(L_t(j)) \right], \tag{12}$$

where β is the discount factor, C_t denotes consumption, D_t is deposits, H_t is the housing stock[8] and L_t is supply of labour. The in-period utility functions are defined as:

$$u(C_t(j)) = z_t^u \left(1 - \frac{b^c}{\pi_{ss}^z}\right) \ln\left[\frac{C_t(j) - b^c C_{t-1}}{1 - b^c/\pi_{ss}^z}\right], \tag{13}$$

$$d(D_t(j)) = z^d \left(1 - \frac{b^d}{\pi_{ss}^z}\right) \ln\left[\frac{D_t(j) - b^d D_{t-1}}{1 - b^d/\pi_{ss}^z}\right], \tag{14}$$

$$v(L_t(j)) = \frac{1 - b^l}{1 + \zeta} \left[\frac{L_t(j) - b^l L_{t-1}}{1 - b^l}\right]^{1+\zeta}, \tag{15}$$

$$w(H_t(j)) = z_t^h \left(1 - \frac{b^h \pi_{ss}^h}{\pi_{ss}^z}\right) \ln\left[\frac{H_t(j) - b_h H_{t-1}}{1 - b^h \pi_{ss}^h/\pi_{ss}^z}\right], \tag{16}$$

where z_t's are preference parameters, of which z_t^u and z_t^h are shocks that follow AR(1) processes.[9] The b-parameters govern habit persistence, and the π_{ss}^z denotes the exogenous steady-state (labour augmenting) technology growth rate.[10] As stated above, the housing sector is assumed to have a weaker technology growth rate that is equal to π_{ss}^z/π_{ss}^h in the steady state (implying that real house prices grow with the value π_{ss}^h in the steady state). The inverse of the Frisch elasticity of labour supply is given by $\zeta > 0$. The Frisch elasticity captures the elasticity of hours worked to the wage rate. The log in-period utility functions for consumption, deposits and housing imply an intertemporal elasticity of substitution equal to 1, which secures a balanced growth path.

[8] The terms housing, housing services and housing stock are used interchangeably throughout this paper. In the same way as in Iacoviello and Neri (2010), one can think of H_t as both housing services and as the housing stock required to produce housing services. Consider a simple housing technology producing housing services, $\mathcal{H} = H_t^{\kappa_t}$, where κ_t is a time-varying elasticity of housing services to the housing stock. In such a setup, the total effects from the housing stock to the utility of the consumer will be captured both through the housing technology shock κ_t and the housing preference shock z_t^h. Hence, as we do not include κ_t in our model, the housing preference shock captures both pure preference shocks and changes in housing service technology.

[9] Most shock processes are modelled as log-deviations from their steady state.

[10] Including a habit formation parameter on hours worked turns out to have very limited impact on the properties of the model.

$$
\begin{aligned}
&P_t C_t(j) + P_t D_t(j) + P_t^H H_t(j) + \left(r_{t-1}^F + \delta_t^B(j)\right) P_{t-1} B_{h,t-1}(j) \\
&\quad = W_t(j) L_t(j)\left[1-\gamma_t(j)\right] + P_t I_{B,t}(j) + R_{t-1}^d P_{t-1} D_{t-1}(j) \\
&\qquad + (1-\delta_H) P_t^H H_{t-1}(j) + DIV_t(j) - TAX_t(j),
\end{aligned} \tag{17}
$$

where P_t is the price level of final goods, P_t^H is the price level of housing services, r_t^F is the nominal net mortgage interest rate faced by households, R_t^d is the gross interest on household's deposits, $\delta_t^B(j)$ denotes household j's amortisation rate (mortgage repayment share), $B_{h,t}(j)$ is real household borrowing (or mortgage), $W_t(j)$ is the nominal wage rate (in both the intermediate goods sector and the oil sector) set by household j, $\gamma_t(j)$ is the wage adjustment cost (defined below in (22)), $L_t(j)$ is the total amount of hours worked (in both the intermediate goods sector and the oil sector), $I_{B,t}(j)$ indicates new real loans by household j, δ_H denotes the depreciation rate of the housing stock and $DIV_t(j)$ and $TAX_t(j)$ are dividends[11] (in nominal terms) disbursed to household j and lump-sum taxes payed by household j, respectively. Hence, equation (17) states that expenditures on consumption, deposits, housing services as well as interest and principal on the mortgage, need to be equal to the sum of labour income (net of adjustment costs), new mortgage, deposits from the previous period with interest income, undepreciated housing stock plus any dividends (and other lump-sum income) less taxes.

Household borrowing follows the process:

$$
B_{h,t}(j) = \left(1 - \delta_t^B(j)\right) \frac{P_{t-1}}{P_t} B_{h,t-1}(j) + I_{B,t}(j). \tag{18}
$$

Similar to Iacoviello (2005) and Gelain et al. (2017b), we assume that households are credit constrained. Specifically, we assume that household j's new loans, $I_{B,t}$, are constrained by the expected housing wealth (the expected household's housing stock in the next period less mortgage), assumed to always be binding:[12]

$$
I_{B,t}(j) = \phi_t E_t\left[\frac{P_{t+1}^H}{P_{t+1}} \frac{P_{t+1}}{P_t} H_t(j) - B_{h,t}(j)\right], \tag{19}
$$

[11] Including any entrepreneurial surplus (see Section D.5).

[12] Our setup is inspired by and very similar to Gelain et al. (2017b) except this study assumes that the households refinance a fixed fraction of the mortgage in every period, collateralised by the same fraction of their housing wealth.

where ϕ_t is the collateral coefficient that governs the constraint on new household loans. It follows an AR(1) process and can be interpreted as a shock to the loan-to-value (LTV) ratio for household borrowing. As house prices increase, the collateral values of houses rise. This expands households' capacity to borrow more and thus create a demand for mortgages, the proceeds of which are spent on consumption goods, housing and deposits. In the steady-state solution of the model, Kravik et al. (n.d.) derives the relationship between ϕ_t and the LTV in the steady state.

We follow Gelain et al. (2017b) in that the loan principal repayment share follows from an (approximated) annuity loan repayment formula:

$$\delta_{t+1}^{B}(j) = \left(1 - \frac{I_{B,t}(j)}{B_{h,t}(j)}\right)\left(\delta_{t}^{B}(j)\right)^{\alpha^h} + \frac{I_{B,t}(j)}{B_{h,t}(j)}\left(1-\alpha^h\right)^{\kappa^h}, \tag{20}$$

where α^h and κ^h are exogenous parameters that govern the dynamics of amortisation rate. In the case of α^h equal to 0, $\delta_t^B(j) = 1$ for all t, i.e. $B_{h,t}(j) = I_{B,t}(j)$, but if $\alpha^h > 0$, the above repayment formula captures the fact that the amortisation rate is low during the first years after taking up a mortgage when interest payments are high and increases thereafter. We calibrate α^h and κ^h to capture the repayment schedule of a typical mortgage contract of 30 years.

The labour market is characterised by monopolistic competition. Households supply labour and set wages subject to demand from the intermediate goods sector and the oil supply sector. Real wages are set as a markup over the marginal rate of substitution of consumption for leisure (see first-order conditions below). As there is assumed to be full labour mobility between the two sectors, there is only one wage level in the economy. Household j faces the following labour demand curve from the intermediate goods sector and the oil sector:

$$L_t(j) = \left(\frac{W_t(j)}{W_t}\right)^{-\psi_t} L_t, \tag{21}$$

where W_t is the wage rate and ψ_t is the elasticity of substitution between differentiated labour, which follows an AR(1) process and can be interpreted as an inverse wage markup shock.[13] We

[13]For the model to be able to replicate the importance of the oil sector for the Norwegian economy, we have added a direct impact from the oil price and the labour demand from oil supply firms to the wage markup shock. In Norway, collective wage bargaining is conducted in a way to promote competitiveness for the export-oriented sector, i.e. meaning that export-oriented industries negotiate before other labour groups and thereby set the norm for other industries. This wage bargaining system is referred to as *Frontfagsmodellen* ("leading sector model"), which suggests the export-oriented sector has more bargaining power than their relative labour share would imply. In NEMO, we implement this feature through the wage markup shock.

further assume that there is sluggish wage adjustment due to adjustment costs that are measured in terms of the total wage bill (cf. Kim (2000)). Wage adjustment costs are specified as:

$$\gamma_t(j) = \frac{\phi^W}{2}\left[\frac{W_t(j)/W_{t-1}(j)}{W_{t-1}/W_{t-2}} - 1\right]^2. \tag{22}$$

As can be seen from (22), costs are related to changes in individual wage inflation relative to the past observed rate for the whole economy.[14] The parameter $\phi^W > 0$ determines how costly it is to change the wage inflation rate.

Combining (18) with (19), and (18) with (20) give the borrowing constraint and the repayment constraint, respectively:

$$B_{h,t}(j) = \frac{\left(1-\delta_t^B(j)\right)}{1+\phi_t}\frac{P_{t-1}}{P_t}B_{h,t-1}(j) + \frac{\phi_t}{1+\phi_t}E_t\left[\frac{P_{t+1}^H}{P_{t+1}}\frac{P_{t+1}}{P_t}H_t(j)\right], \tag{23}$$

$$\delta_{t+1}^B(j) = \left(1-\delta_t^B(j)\right)\frac{P_{t-1}}{P_t}\frac{B_{h,t-1}(j)}{B_{h,t}(j)}\left[\left(\delta_t^B(j)\right)^{\alpha^h} - \left(1-\alpha^h\right)^{\kappa^h}\right] + \left(1-\alpha^h\right)^{\kappa^h}. \tag{24}$$

Maximizing utility, (12), subject to the budget constraint, (17); the borrowing constraint, (23) and the repayment constraint, (24), letting ω_t and μ_t be the Lagrangian multipliers associated with (23) and (24), gives the first-order conditions with respect to real borrowing, $B_{h,t}$ (25); deposits, D_t (26); the wage rate, W_t (27); housing, H_t (28); and repayments, δ_t^B (29) (defining the stochastic discount factor as $\Delta_{t+1} \equiv \beta\frac{u'(C_{t+1})}{u'(C_t)}\frac{P_t}{P_{t+1}}$ and suppressing household indicator j):

$$\begin{aligned}
&1 - E_t[\Delta_{t+1}]R_t^F - \frac{\omega_t}{u'(C_t)} \\
&+E_t\left[\frac{\omega_{t+1}}{u'(C_{t+1})}\Delta_{t+1}\frac{(1-\delta_{t+1}^B)}{1+\phi_{t+1}}\right] \\
&-\frac{\mu_t}{u'(C_t)}\frac{B_{h,t-1}}{B_{h,t}^2}\frac{P_{t-1}}{P_t}(1-\delta_t^B)\left[\left(\delta_t^B\right)^{\alpha^h} - (1-\alpha^h)^{\kappa^h}\right] \\
&+E_t\left[\frac{\mu_{t+1}}{u'(C_{t+1})}\Delta_{t+1}\frac{(1-\delta_{t+1}^B)}{B_{h,t+1}}\left[\left(\delta_{t+1}^B\right)^{\alpha^h} - (1-\alpha^h)^{\kappa^h}\right]\right] = 0,
\end{aligned} \tag{25}$$

$$E_t[\Delta_{t+1}]R_t^d - 1 = -\frac{d'(D_t)}{u'(C_t)}, \tag{26}$$

[14] In NEMO, the adjustment costs of wages and prices are fully indexed, which has been the case in NEMO since it was first introduced. Different specifications of adjustment costs will be explored in the future.

$$
\begin{aligned}
\frac{v'\left(L_t\right)}{u'\left(C_t\right)}\psi_t\frac{P_t}{W_t} = & \left[\left(\psi_t - 1\right)\left(1-\gamma_t\right) + \phi^W\left(\frac{W_t/W_{t-1}}{W_{t-1}/W_{t-2}} - 1\right)\frac{W_t/W_{t-1}}{W_{t-1}/W_{t-2}}\right] \\
& -E_t\left[\Delta_{t+1}\frac{L_{t+1}}{L_t}\phi^W\left(\frac{W_{t+1}/W_t}{W_t/W_{t-1}} - 1\right)\frac{\left(W_{t+1}/W_t\right)^2}{W_t/W_{t-1}}\right],
\end{aligned}
\tag{27}
$$

$$
\frac{w'(H_t)}{u'\left(C_t\right)} = \frac{P_t^H}{P_t} - \left(1-\delta_H\right)E_t\left[\Delta_{t+1}\frac{P_{t+1}^H}{P_t}\right] - \frac{\omega_t}{u'\left(C_t\right)}\frac{\phi_t}{1+\phi_t}E_t\left[\frac{P_{t+1}^H}{P_{t+1}}\frac{P_{t+1}}{P_t}\right],
\tag{28}
$$

$$
\begin{aligned}
-\mu_{t-1} + \mu_t\beta\frac{B_{h,t-1}}{B_{h,t}}\frac{P_{t-1}}{P_t} & \left[\alpha^h\left(\delta_t^B\right)^{\alpha^h-1}\left(1-\delta_t^B\right) - \left(\delta_t^B\right)^{\alpha^h} + \left(1-\alpha^h\right)^{\kappa^h}\right] \\
& -\omega_t\beta\left[\frac{B_{h,t-1}}{1+\phi_t}\frac{P_{t-1}}{P_t}\right] = 0.
\end{aligned}
\tag{29}
$$

In the special case of $\delta_t^B = 1$, i.e. when the full mortgage is rolled over in every period, the first-order condition with respect to $B_{h,t}$, equation (25), would simply collapse to the first three terms: $E_t[\Delta_{t+1}]R_t^F = 1 - \frac{\omega_t}{u'(C_t)}$, i.e. households would borrow up to a point where the effective cost of borrowing is equal to the shadow marginal benefit of mortgage. When $\delta_t^B < 1$, the fourth term in (25) captures that an increased mortgage in the current period also increases the mortgage in future periods (due to the long-term debt contracts). The last two terms control how the path of the amortisation rate changes when the size of the mortgage increases marginally.

The optimality condition for deposits, equation (26), states that the marginal rate of substitution between deposits and consumption must be equal to the marginal benefit of holding deposits (the interest rate). Compared with a canonical DSGE model, household faces an additional opportunity cost of consuming in the current period in the form of lost utility from deposits.

Equation (27) is the first-order equation with respect to the wage rate, which is set by households subject to the demand function in (21). In the special case without any wage adjustment costs, $\phi^W = \gamma_t = 0$ (see equation (22)), (27) will simply be reduced to $\frac{W_t}{P_t} = \frac{\psi_t}{\psi_t - 1}\frac{v'(L_t)}{u'(C_t)}$, i.e., the real wage rate will be set as a markup over the marginal rate of substitution between leisure and consumption. The second term on the right-hand side of (27) captures the adjustment costs of a change in wages, whereas the last term reflects that increasing wages today reduces the need to increase wages in the future. Thus, the latter term means that households consider the full path of future labour demand when setting the current wage level.

The first-order condition with respect to housing, (28), equalises the marginal rate of substitution between housing and consumption with the effective price of housing. The first term on the right-hand side is the real house price, the second part is the net-of-depreciation continuation value, and the last term captures that the increase in the household's collateral from more housing induces the household to take up more mortgage debt (from equation (19)). The increase in collateral is valued at the shadow value of additional mortgage debt.

Equation (29) is the first-order condition with respect to mortgage repayments, δ_t^B. The second term shows the impact on the amortisation dynamics when the current repayment rate is increased marginally, whereas the last term includes the indirect effects through the behaviour of the mortgage.

D.2.2 House price expectations

Agents in NEMO are forward-looking and have model-consistent expectations. For instance, workers decide on wages and labour supply not only based on today's consumer prices and labour demand curves, but also based on all future expected prices and demand curves. The same is true for all agents of the model, regarding all prices. A noteworthy exception is house price expectations, where we introduce so-called hybrid expectations as in Gelain et al. (2013). We assume that a share b^{sa} of households expects house prices to follow a moving average process (i.e. partly backward-looking expectations), whereas a share $(1 - b^{sa})$ has rational expectations (in log-gap form). This generates house price cycles more in line with empirical observations:

$$E_t \left[\widehat{P^H_{t+1}} \right] = b^{sa} \widehat{X^H_t} + (1 - b^{sa}) \widehat{P^H_{t+1}}, \tag{30}$$

where $\widehat{\ }$ denotes gap-form and the moving average process is defined as

$$\widehat{X^H_t} = \lambda^{sa} \widehat{P^H_{t-1}} + (1 - \lambda^{sa}) \widehat{X^H_{t-1}}. \tag{31}$$

D.3 Intermediate goods sector

A continuum of firms in the intermediate goods sector uses capital and labour to produce a differentiated intermediate good which is sold under monopolistic competition to the final goods producers at home and abroad as an export. Firms choose labour and capital services to minimise factor outlays, taking wages and rental rates of capital as given. As firms in the intermediate goods sector enjoy market power, they set prices as a markup over marginal costs, and they charge different prices at home and abroad.[15] Firms are assumed to face so-called Rotemberg adjustment costs when changing nominal prices (Rotemberg, 1982), which lead firms to change their prices less in response to shocks than they otherwise would have done, i.e. prices are sticky. This assumption contributes to the non-neutrality of monetary policy. Since changing prices is costly, firms must take into account future developments when deciding on today's prices. Hence, inflation expectations influence today's inflation. Finally, capital is produced by capital producers (see Section D.6).

D.3.1 The maximisation problem

The intermediate firm n sells good $Q_t(n)$ to the final goods sector and exports the amount $M_t^*(n)$, where $T_t(n) = Q_t(n) + M_t^*(n))$. It has the following constant elasticity of substitution (CES) production function:

$$T_t(n) = \left[(1-\alpha)^{\frac{1}{\xi}} \left(Z_t z_t^L L_{I,t}(n)\right)^{1-\frac{1}{\xi}} + \alpha^{\frac{1}{\xi}} \overline{K}_{I,t}(n)^{1-\frac{1}{\xi}}\right]^{\frac{\xi}{\xi-1}}, \tag{32}$$

where $\alpha \in [0,1]$ determines the capital share and ξ denotes the elasticity of substitution between labour and capital. The variables $L_{I,t}(n)$ and $\overline{K}_{I,t}(n)$ denote, respectively, hours and effective capital used by firm n in period t. There are two exogenous shocks to productivity in the model: Z_t refers to an exogenous permanent labour augmenting process, which grows at the gross rate π_t^z, whereas z_t^L denotes a temporary (stationary) shock to productivity (or labour utilisation) that follows an AR(1) process.

Total labour input to firm n is an index over used labour from all households j, i.e.

$$L_{I,t}(n) = \left[\int_0^1 L_{I,t}(n,j)^{1-\frac{1}{\psi_t}} dj\right]^{\frac{\psi_t}{\psi_t-1}}, \tag{33}$$

where ψ_t denotes the elasticity of substitution between differentiated labour types.

Let $W_{I,t}$ be the wage rate, which is equal to W_t due to perfect labour mobility, and let $R_{KI,t}$ be the rental rate of capital equal to $R_{K,t}$ due to perfect capital mobility. Minimising total factor

[15] Hence, we assume local currency pricing as in Devereux and Engel (2003) and Corsetti and Dedola (2005).

outlays gives rise to the following conditional factor demand functions:[16]

$$L_{I,t} = (1-\alpha)\left(\frac{W_{I,t}}{MC_t}\right)^{-\xi} T_t(Z_t z_t^L)^{\xi-1}, \tag{34}$$

$$\overline{K}_{I,t} = \alpha\left(\frac{R_{KI,t}}{MC_t}\right)^{-\xi} T_t, \tag{35}$$

where we have used that marginal costs can be shown to be:

$$MC_t = \left[(1-\alpha)\left(\frac{W_{I,t}}{Z_t z_t^L}\right)^{1-\xi} + \alpha R_{KI,t}^{1-\xi}\right]^{\frac{1}{1-\xi}}. \tag{36}$$

This means, for example, that higher real wages will reduce labour demand and increase the demand for capital for a given level of production. A proportional increase in both real wages and rental prices will have no impact on the demand for labour and capital. Firms face the following price adjustments costs in the domestic and foreign markets, respectively:

$$\gamma_{PQ,t}(n) \equiv \frac{\phi^{PQ}}{2}\left[\frac{P_t^Q(n)/P_{t-1}^Q(n)}{P_{t-1}^Q/P_{t-2}^Q} - 1\right]^2, \tag{37}$$

$$\gamma_{PM^*,t}(n) \equiv \frac{\phi^{PM^*}}{2}\left[\frac{P_t^{M^*}(n)/P_{t-1}^{M^*}(n)}{P_{t-1}^{M^*}/P_{t-2}^{M^*}} - 1\right]^2, \tag{38}$$

where P_t^Q and $P_t^{M^*}$ are the prices in the domestic and the foreign market (in foreign currency), respectively. The costs of changing prices are governed by the parameters ϕ^{PQ} and ϕ^{PM^*}.[17] One can show that the firms face the following demand functions from the final goods sector and from abroad, respectively:

$$Q_t(n) = \left(\frac{P_t^Q(n)}{P_t^Q}\right)^{-\theta_t^H} Q_t, \tag{39}$$

$$M_t^*(n) = \left(\frac{P_t^{M^*}(n)}{P_t^{M^*}}\right)^{-\theta^{F^*}} M_t^*, \tag{40}$$

[16] Note that in symmetric equilibrium all firms make the same decisions, hence $L_{I,t}(n) = L_{I,t}$, and similarly for the capital demand.

[17] Similar to wage adjustment costs, price adjustment costs are related to changes in inflation for firm n relative to the past observed rate for the whole economy.

where θ_t^H is the elasticity of substitution between domestic goods produced by different firms in the intermediate goods sector and follows an AR(1) process, which can be interpreted as a domestic price (inverse) markup shock. Correspondingly, θ^{F^*} is the elasticity of substitution across export goods.

Profit maximisation gives rise to the following first-order condition for price-setting in the domestic market, P_t^Q:

$$\begin{aligned} &Q_t - \theta_t^H Q_t + MC_t \theta_t^H \frac{Q_t}{P_t^Q} - \phi^{PQ} \left[\frac{P_t^Q / P_{t-1}^Q}{P_{t-1}^Q / P_{t-2}^Q} - 1 \right] \frac{P_t^Q / P_{t-1}^Q}{P_{t-1}^Q / P_{t-2}^Q} Q_t \\ &+ E_t \left\{ \Delta_{t+1} \phi^{PQ} \left[\frac{P_{t+1}^Q / P_t^Q}{P_t^Q / P_{t-1}^Q} - 1 \right] \frac{(P_{t+1}^Q / P_t^Q)^2}{P_t^Q / P_{t-1}^Q} Q_{t+1} \right\} = 0, \end{aligned} \tag{41}$$

In the absence of adjustment costs, $\phi^{PQ} = 0$, prices would simply be set as a markup over marginal costs in every period $P_t^Q = \frac{\theta_t^H}{\theta_t^H - 1} MC_t$ (where $\theta_t^H > 1$). The fourth term captures the adjustment costs of the price change, whereas the last term reflects that increasing the price in the current period reduces the need to increase prices more in the future. Hence, the latter term implies that firms consider the full path of future demand when setting prices.

Similarly, the first-order condition with respect to $P_t^{M^*}(n)$ can be written as

$$\begin{aligned} &S_t M_t^* - \theta^{F^*} S_t M_t^* + MC_t \theta^{F^*} \frac{M_t^*}{P_t^{M^*}} - \phi^{PM^*} \left[\frac{P_t^{M^*} / P_{t-1}^{M^*}}{P_{t-1}^{M^*} / P_{t-2}^{M^*}} - 1 \right] \frac{P_t^{M^*} / P_{t-1}^{M^*}}{P_{t-1}^{M^*} / P_{t-2}^{M^*}} S_t M_t^* \\ &+ E_t \left\{ \Delta_{t+1} \phi^{PM^*} \left[\frac{P_{t+1}^{M^*} / P_t^{M^*}}{P_t^{M^*} / P_{t-1}^{M^*}} - 1 \right] \frac{\left(P_{t+1}^{M^*} / P_t^{M^*} \right)^2}{P_t^{M^*} / P_{t-1}^{M^*}} S_{t+1} M_{t+1}^* \right\} = 0, \end{aligned} \tag{42}$$

where S_t is the nominal exchange rate in foreign currency per Norwegian krone (an increase in S_t implies a depreciation of the Norwegian krone). In the special case of $\phi^{PM^*} = 0$, equation (42) would become: $P_t^{M^*} = \frac{\theta^{F^*}}{\theta^{F^*} - 1} \frac{MC_t}{S_t}$.

D.4 Final goods sector

The final goods sector combines imported goods M_t and domestic goods Q_t to produce a final good A_t that is sold at a price P_t. The final good can be used for consumption, investments, government consumption and input to the oil supply firms.

$$A_t = \left(\nu_t^{\frac{1}{\mu}} Q_t^{1-\frac{1}{\mu}} + (1-\nu_t)^{\frac{1}{\mu}} M_t^{1-\frac{1}{\mu}} \right)^{\frac{\mu}{\mu-1}}, \tag{43}$$

where ν_t is the domestic goods share and μ is the elasticity of substitution between domestic and imported goods. ν_t represents the degree of home bias. It follows an AR(1) process and can be interpreted as an import demand shock. The domestic good Q_t is a composite of domestic goods produced by the different firms in the intermediate goods sector. The imported good M_t is a composite of imported goods produced by the different firms in the intermediate goods sector abroad.

Minimising costs gives rise to the following conditional demand functions:

$$Q_t = \nu_t \left(\frac{P_t^Q}{P_t} \right)^{-\mu} A_t, \tag{44}$$

$$M_t = (1-\nu_t) \left(\frac{P_t^M}{P_t} \right)^{-\mu} A_{t,} \tag{45}$$

where $P_t \equiv \left[\nu_t (P_t^Q)^{1-\mu} + (1-\nu_t)(P_t^M)^{1-\mu} \right]^{\frac{1}{1-\mu}}$ is the numerator of the model.

D.5 Entrepreneurs

D.5.1 The maximisation problem

In this sector we focus on the maximisation problem for entrepreneurs. Entrepreneurs are households, but this section considers a separate part of households' budget constraint to simplify the exposition.[18] We could alternatively have modelled this sector as a firm owned by households.

Entrepreneurs rent capital to the intermediate goods sector and the oil sector gaining the rental rate $R_{K,t}$ $(= R_{KI,t} = R_{KO,t}$ due to perfect capital mobility). They rent out $\overline{K}_{I,t}$ to the intermediate goods sector and $\overline{K}_{O,t}$ to the oil supply sector. $\overline{K}_t$ is then the aggregate utilised capital rented out by entrepreneurs. At the beginning of period t they sell the non-depreciated capital $(1-\delta)\, K_{t-1}$ at price P_t^K to the capital producers. The latter combine it with investment goods to produce K_t to be sold back to entrepreneurs at the same price. To finance their activity,

[18]We suppress index j in this section.

entrepreneurs borrow $B_{e,t}$ (referred to as corporate credit) from banks at gross rate R_t^e, providing capital goods as collateral. They enter into a multi-period loan contract. Finally, entrepreneurs also decide the capital utilisation rate u_t.

We define effective capital input in period t as

$$\overline{K}_t = u_t K_{t-1}. \tag{46}$$

Entrepreneurs are subject to the following real budget constraint:

$$\begin{gathered} \frac{R_{K,t}}{P_t}\overline{K}_t + \frac{P_t^K}{P_t}(1-\delta)K_{t-1} + I_{B,t}^e = \\ \frac{P_t^K}{P_t}K_t + (r_{t-1}^e + \delta_t^e)\frac{P_{t-1}}{P_t}B_{e,t-1} + \gamma(u_t)K_{t-1} + C_t + \frac{1}{P_t}\Xi_t, \end{gathered} \tag{47}$$

where the first term is the income from renting out capital to the intermediate goods sector and the oil supply sector, the second term is the income generated from the sale of non-depreciated capital to the capital producers (see Section D.6), and $I_{B,t}^e$ is new loans. The first term on the expenditure side of (47) is capital bought back from the capital producers, the second term represents the interest and principal payments to banks on outstanding debt, the third term are costs associated with a given level of the utilisation rate of capital (see below), and C_t is household consumption. The last term, Ξ_t, represents all other terms that enter into the household budget constraint (17).[19]

The unit utilisation cost is defined as

$$\gamma(u_t) = \frac{R_{K,ss}}{P_{ss}\phi_u}\left[e^{\phi_u(u_t-1)} - 1\right], \tag{48}$$

where ϕ_u governs the cost of adjusting the utilisation rate, and the subscript ss denotes steady-state values. Note that total utilised capital rented out must be equal to the utilised capital demanded by the intermediate goods sector and by the oil supply sector, $\overline{K}_t = \overline{K}_{I,t} + \overline{K}_{O,t}$.

Whereas households used housing capital as collateral, the entrepreneurs can borrow against

[19]Since households and entrepreneurs technically are the same, one can think of all terms in (47) (except C_t and Ξ_t) as part of DIV_t in (17).

their real capital $(1-\delta) K_t$. Similar to the household constraint (23) and (24), we have:

$$B_{e,t} = \frac{(1-\delta_t^e)}{1+\phi_t^{ent}} \frac{P_{t-1}}{P_t} B_{e,t-1} + \frac{\phi_t^{ent}}{1+\phi_t^{ent}} E_t \left[\frac{P_{t+1}^K}{P_{t+1}} \frac{P_{t+1}}{P_t} (1-\delta) K_t \right], \tag{49}$$

$$\delta_{t+1}^e = (1-\delta_t^e) \frac{P_{t-1}}{P_t} \frac{B_{e,t-1}}{B_{e,t}} \left[(\delta_t^e)^{\alpha^e} - (1-\alpha^e)^{\kappa^e} \right] + (1-\alpha^e)^{\kappa^e}, \tag{50}$$

where ϕ_t^{ent} is the collateral coefficient that governs the constraint on new corporate debt. It follows an AR(1) process and can be interpreted as a shock to the LTV ratio for business credit. δ_t^e is the loan repayment share and α^e and κ^e are exogenous parameters that govern entrepreneurs' annuity loan repayment formula (analogous to the household case in equation (20)).

Maximising utility (equation (12)) subject to (47), (49) and (50) with respect to K_t, B_t^e, δ_t^e and u_t gives the following first-order conditions (where ω_t^e and μ_t^e are the Lagrangian multipliers associated with (49) and (50), respectively):

$$\begin{aligned} \frac{P_t^K}{P_t} &= E_t \left[\frac{\omega_t^e}{u'(C_t)} \frac{\phi_t^{ent}}{1+\phi_t^{ent}} \frac{P_{t+1}^K}{P_{t+1}} \frac{P_{t+1}}{P_t} (1-\delta) \right] \\ &+ E_t \left[\Delta_{t+1} \frac{P_{t+1}}{P_t} \left(\frac{P_{t+1}^K}{P_{t+1}} (1-\delta) + \frac{R_{K,t+1}}{P_{t+1}} u_{t+1} - \gamma(u_{t+1}) \right) \right], \end{aligned} \tag{51}$$

$$\begin{aligned} & B_{e,t} - B_{e,t} E_t [\Delta_{t+1}] R_t^e - \frac{\omega_t^e}{u'(C_t)} B_{e,t} \\ & + E_t \left[\frac{\omega_{t+1}^e}{u'(C_{t+1})} \Delta_{t+1} \frac{(1-\delta_{t+1}^e)}{1+\phi_{t+1}^{ent}} B_{e,t} \right] \\ & - \frac{\mu_t^e}{u'(C_t)} \frac{B_{e,t-1}}{B_{e,t}} \frac{P_{t-1}}{P_t} (1-\delta_t^e) \left[(\delta_t^e)^{\alpha^e} - (1-\alpha^e)^{\kappa^e} \right] \\ & + E_t \left[\frac{\mu_{t+1}^e}{u'(C_{t+1})} \Delta_{t+1} \frac{B_{e,t}}{B_{e,t+1}} (1-\delta_{t+1}^e) \left[(\delta_{t+1}^e)^{\alpha^e} - (1-\alpha^e)^{\kappa^e} \right] \right] = 0, \end{aligned} \tag{52}$$

$$\begin{aligned} & -\mu_{t-1}^e + \mu_t^e \beta \frac{B_{e,t-1}}{B_{e,t}} \frac{P_{t-1}}{P_t} \left[\alpha^e (\delta_t^e)^{\alpha^e - 1} (1-\delta_t^e) - (\delta_t^e)^{\alpha^e} + (1-\alpha^e)^{\kappa^e} \right] \\ & - \omega_t^e \beta \left[\frac{B_{e,t-1}}{1+\phi_t^{ent}} \frac{P_{t-1}}{P_t} \right] = 0, \end{aligned} \tag{53}$$

$$\frac{R_{K,t}}{P_t} = \gamma'(u_{,t}) = \frac{R_{K,ss}}{P_{ss}} e^{\phi_u (u_t - 1)}. \tag{54}$$

Equation (51), the first-order condition with respect to K_t, states that entrepreneurs choose capital so that the marginal utility of capital (right side of (51)) equals marginal costs (the left side). The first term on the right side represents the benefit of increased collateral whereas the second term is the income from selling and renting out capital net of utilisation costs.

The optimality conditions for corporate credit (52) and for loan repayments (53) are fully analogues to (25) and (29) in the household section, respectively.

Equation (54) is the first-order condition with respect to the utilisation rate, u_t, which states that the marginal benefit of utilising an additional unit of capital is equal to the cost of utilising it. The second equality follows from (48).

D.6 Capital producers

Capital goods, K_t, are produced by separate producers. At the beginning of period t the capital goods producers buy undepreciated capital $(1-\delta)\,K_{t-1}$ at price P_t^K from entrepreneurs, and combines it with (gross) investment goods $I_{C,t}$ to produce K_t to be sold back to entrepreneurs at the same price. The capital producers operate in a perfectly competitive market, and therefore earn no profit. $I_{C,t}$ is bought from the final goods sector at a price P_t.

The representative capital producer h maximises the following function

$$\max_{\{I_{C,t}(h)\}} \left[P_t^K K_t(h) - P_t^K\,(1-\delta)\,K_{t-1}(h) - P_t I_{C,t}(h)\right],$$

s.t. the capital accumulation equation:

$$K_t(h) = (1-\delta)K_{t-1}(h) + \kappa_t(h)K_{t-1}(h). \tag{55}$$

The last term, $\kappa_t(h)K_{t-1}(h)$, can be thought of as "net investment", i.e. investment net of adjustment costs:

$$\kappa_t(h) = \frac{I_{C,t}(h)}{K_{t-1}(h)} - \frac{\phi_{I1}}{2}\left[\frac{I_{C,t}(h)}{K_{t-1}(h)} - \frac{I_{C,ss}\pi_{ss}^z}{K_{ss}} z_{I,t}\right]^2 - \frac{\phi_{I2}}{2}\left[\frac{I_{C,t}(h)}{K_{t-1}(h)} - \frac{I_{C,t-1}}{K_{t-2}}\right]^2. \tag{56}$$

The parameters ϕ_{I1} and ϕ_{I2} govern the degree of adjustment costs, and $z_{I,t}$ is a shock to investment adjustment costs, that follows an AR(1) process. Note that there are two terms in the adjustment cost equation. The first cost term stems from the deviation of today's level of investment from its (stationary) steady-state value (where π_{ss}^z is steady-state technology growth (see page 64)), whereas the second cost term originates from the deviation of today's level of investment from the level in the previous period (for the whole economy). Because of these adjustment costs, net investment is smaller than gross investment, $\kappa_t K_{t-1} \leq I_{C,t}$ (holds with equality in the steady state).

Maximisation with respect to $I_{C,t}$ gives the following first-order condition, suppressing indicator h:

$$\frac{P_t^K}{P_t} = \left\{1 - \phi_{I1}\left[\frac{I_{C,t}}{K_{t-1}} - \frac{I_{C,ss}\pi_{ss}^z}{K_{ss}} z_{I,t}\right] - \phi_{I2}\left[\frac{I_{C,t}}{K_{t-1}} - \frac{I_{C,t-1}}{K_{t-2}}\right]\right\}^{-1}. \tag{57}$$

Based on the movements in the adjustment costs in the two bracketed terms in (57), the real price of capital fluctuates around its steady-state level of 1.

D.7 Housing producers

The housing producers' production function and housing capital accumulation constraint are similar to those of the capital producers. At the beginning of period t, the housing producers buy the undepreciated housing stock $(1-\delta_H) H_{t-1}$ at price P_t^H from households, and combine it with housing investment goods $I_{H,t}$ to produce H_t to be sold back to households at the same price. The housing producers also operate in a perfectly competitive market and earn no profit. $I_{H,t}$ is bought from the final goods sector at a price P_t.

Consistent with the historical trend in real house prices, the housing sector is assumed to have a weaker technology growth rate than the rest of the economy of π_t^z/π_t^h, where $\pi_t^z \equiv Z_t/Z_{t-1}$ and $\pi_t^h \equiv Z_t^h/Z_{t-1}^h$.

The representative housing producer f maximises

$$\max_{\{I_{H,t}(f)\}} \left[P_t^H H_t(f) - P_t^H (1-\delta_H) H_{t-1}(f) - P_t I_{H,t}(f)\right],$$

s.t. the housing accumulation equation:

$$H_t(f) = (1-\delta_H)H_{t-1}(f) + \gamma_{H,t}(f)H_{t-1}(f), \tag{58}$$

where $\gamma_{H,t}(f)H_{t-1}(f)$ is "net housing investment" and $\gamma_{H,t}(f)$ is defined as

$$\begin{aligned}\gamma_{H,t}(f) = \frac{I_{H,t}(f)}{H_{t-1}(f)Z_t^h} - \frac{\phi_{H1}}{2}\left[\frac{I_{H,t}(f)}{H_{t-1}(f)Z_t^h} - \frac{I_{H,ss}\pi_{ss}^z}{H_{ss}\pi_{ss}^h} z_{IH,t}\right]^2 \\ - \frac{\phi_{H2}}{2}\left[\frac{I_{H,t}(f)}{H_{t-1}(f)Z_t^h} - \frac{I_{H,t-1}}{H_{t-2}Z_{t-1}^h}\right]^2.\end{aligned} \tag{59}$$

The parameters ϕ_{H1} and ϕ_{H2} govern the degree of adjustment costs, and $z_{IH,t}$ is a shock to housing investment adjustment costs, that follows an AR(1) process. The interpretation of the investment adjustment cost function is similar to the one in the previous section.

The first-order condition with respect to $I_{H,t}$ becomes, analogously to (57) (suppressing index f):

$$\frac{P_t^H}{P_t} = Z_t^h\left(1 - \phi_{H1}\left[\frac{I_{H,t}}{H_{t-1}Z_t^h} - \frac{I_{H,ss}\pi_{ss}^z}{H_{ss}\pi_{ss}^h} z_{IH,t}\right] - \phi_{H2}\left[\frac{I_{H,t}}{H_{t-1}Z_t^h} - \frac{I_{H,t-1}}{H_{t-2}Z_{t-1}^h}\right]\right)^{-1}. \tag{60}$$

D.8 Banking sector

The structure of the banking sector builds on Gerali et al. (2010). There is an infinite number of banks in the economy, indexed by $i \in [0, 1]$. Each bank consists of two retail branches and a wholesale branch. One retail branch is responsible for providing differentiated loans to households and to entrepreneurs, while the other retail branch specialises in deposits. Both branches set interest rates in a monopolistically competitive fashion (Hafstead and Smith, 2012), subject to adjustment costs, which leads to imperfect and sluggish interest rate pass-through from the policy rate to loan and deposit rates. The wholesale branch manages the capital position of the bank. It chooses the overall level of operations regarding deposits and lending, adhering to Gerali et al. (2010)-type capital requirements adjusted with asset specific risk weights. Banks incur a cost if they fail to meet their capital-to-asset ratio target. Bank capital plays an important role for credit supply in the model through a feedback loop between the real and the financial sides of the economy.

The balance sheet of bank i (in real terms) is:

$$B_t(i) = B_{F,t}^{TOT}(i) + K_t^B(i), \tag{61}$$

where $B_t(i)$ is total assets (total lending). On the liability side, $B_{F,t}^{TOT}(i)$ is total external bank funding and $K_t^B(i)$ is bank capital (equity). Total external bank funding is the sum of household deposits and foreign debt, i.e

$$B_{F,t}^{TOT}(i) = D_t(i) + B_t^*(i)\,. \tag{62}$$

Note that $P_t B_t^*(i)$ measures nominal foreign bank debt in domestic currency. Total lending is the sum of lending to entrepreneurs and households:

$$B_t(i) = B_{e,t}(i) + B_{h,t}(i)\,. \tag{63}$$

If banks fail to meet their target level of risk-weighted capital requirements, ϖ_t, they incur a penalty cost. The target level of risk-weighted capital requirements consists of two elements: "hard" capital requirements, γ_t^b and a countercyclical capital buffer, CCB_t^b, hence $\varpi_t = \gamma_t^b + CCB_t^b$.[20] In addition, they face linear operational costs. Profits in period t for bank i as a whole is then given by:

$$\begin{aligned} J_t(i) &= r_t^F(i)\,B_{h,t}(i) + r_t^e(i)\,B_{e,t}(i) - r_t^d(i)\,D_t(i) \\ &- \left(\left[1-\gamma_t^{B^*}\right] R_t^* \frac{S_{t+1}}{S_t} - 1\right) B_t^*(i) - \chi_o B_t(i) - \frac{\chi_c}{2}\left[\frac{K_t^B(i)}{B_t^{RW}(i)} - \varpi_t\right]^2 K_t^B(i), \end{aligned} \tag{64}$$

where $r_t^F(i)$ is the net interest rate on loans to households, $r_t^e(i)$ is the net interest rate on loans to entrepreneurs and $r_t^d(i)$ is the net deposit interest rate. The bank pays a risk premium on foreign funding. The "full" net interest rate for foreign funding hence becomes $\left[1-\gamma_t^{B^*}\right] R_t^* \frac{S_{t+1}}{S_t} - 1$, where $1-\gamma_t^{B^*}$ is the debt-elastic risk premium. R_t^* is the foreign money market rate and S_t is the nominal exchange rate. χ_o governs the operational costs, and χ_c governs the capital target costs. $B_t^{RW}(i)$ denotes risk-weighted assets:

$$B_t^{RW}(i) = \varsigma^e B_{e,t} + \varsigma^h B_{h,t}, \tag{65}$$

where ς^e and ς^h are the risk weights associated with credit to entrepreneurs and households,

[20] The risk-weighted capital requirements, γ_t^b and CCB_t^b, are either shocks that follow AR(1) processes or policy rules that respond to financial variables such as credit or spreads, depending on the policy experiment. They are normally only active when the model is used for financial stability analysis. Otherwise, they are set to their steady-state values.

respectively. Bank capital accumulates according to:

$$K_t^B(i) = (1-\delta^b)\frac{P_{t-1}}{P_t}K_{t-1}^B(i) + \frac{P_{t-1}}{P_t}J_{t-1}(i), \tag{66}$$

where δ^b is the dividend share of the bank capital paid out to shareholders (households).

D.8.1 The wholesale branch

The wholesale branch lends to the loan branch at the interest rate $R_t^{b,e}(i) = 1 + r_t^{b,e}(i)$ for corporate credit (entrepreneurial loans) and $R_t^{b,h}(i) = 1 + r_t^{b,h}(i)$ for household loans. It is funded through borrowing from the deposit branch and from abroad. The "wholesale deposit rate" is assumed to be equal to the money market rate $R_t = 1 + r_t$, which follows from a no-arbitrage condition since we assume that banks have access to unlimited financing at the money market rate. The foreign funding rate, $\left[1-\gamma_t^{B^*}\right]R_t^*\frac{S_{t+1}}{S_t}$, is explained above.

The wholesale branch takes these funding costs as given and solves the following profit maximisation problem:

$$\begin{gathered}\max_{\{B_{h,t}(i),B_{e,t}(i),B_t^*(i),D_t(i)\}} E_t\Big[R_t^{b,e}(i)\,B_{e,t}(i) + R_t^{b,h}(i)\,B_{h,t}(i)\\ -R_tD_t(i) - \left[1-\gamma_t^{B^*}\right]R_t^*\frac{S_{t+1}}{S_t}B_t^*(i) - \chi_oB_t(i) - \frac{\chi_c}{2}\left[\frac{K_t^B(i)}{B_t^{RW}(i)} - \varpi_t\right]^2 K_t^B(i)\Big],\end{gathered} \tag{67}$$

subject to (61) - (63) and (65).

The first-order conditions for the wholesale bank become:[21]

$$R_t^{b,e} = R_t + \chi_o - \chi_c\varsigma^e\left[\frac{K_t^B}{B_t^{RW}} - \varpi_t\right]\left(\frac{K_t^B}{B_t^{RW}}\right)^2, \tag{68}$$

$$R_t^{b,h} = R_t + \chi_o - \chi_c\varsigma^h\left[\frac{K_t^B}{B_t^{RW}} - \varpi_t\right]\left(\frac{K_t^B}{B_t^{RW}}\right)^2, \tag{69}$$

$$R_t = E_t\left[\left[1-\gamma_t^{B^*}\right]R_t^*\frac{S_{t+1}}{S_t}\right]. \tag{70}$$

Hence, the wholesale loan rates, $R_t^{b,e}$ and $R_t^{b,h}$ are set as markups over the money market rate, where the markups are increasing in the linear operational cost and the cost of deviating from

[21] Since all banks behave in the same way, we have removed the index i from the first-order conditions in the banking sector section.

the capital target. The first-order conditions with respect to $D_t(i)$ and $B_t^*(i)$ give equation (70), which is this model's version of the UIP. It says that the money market rate needs to be equal to the "full" interest rate for foreign funding. It is assumed that the risk premium depends positively on the country's net foreign debt position (see Section D.12).

D.8.2 The loan branch

The loan branch lends to households and entrepreneurs (at net rates $r_t^F(i)$ and $r_t^e(i)$, respectively) and borrows from the wholesale branch at the net interest rates $r_t^{b,h}(i)$ and $r_t^{b,e}(i)$. It faces costs when changing the loan rates, governed by the parameters ϕ^F and ϕ^e.

The maximisation problem for the loan branch becomes:

$$\max_{\{r_t^F(i), r_t^e(i)\}} E_s \sum_{t=s}^{\infty} \Delta_{s,t} \left[\begin{array}{c} r_t^F(i) B_{h,t}(i) + r_t^e(i) B_{e,t}(i) - r_t^{b,h}(i) B_{h,t}(i) - r_t^{b,e}(i) B_{e,t}(i) \\ -\frac{\phi^F}{2} \left(\frac{r_t^F(i)}{r_{t-1}^F(i)} - 1 \right)^2 r_t^F B_{h,t} - \frac{\phi^e}{2} \left(\frac{r_t^e(i)}{r_{t-1}^e(i)} - 1 \right)^2 r_t^e B_{e,t} \end{array} \right],$$

subject to

$$B_t(i) = B_{e,t}(i) + B_{h,t}(i), \tag{71}$$

$$B_{h,t}(i) = \left(\frac{r_t^F(i)}{r_t^F} \right)^{-\theta_t^{IH}} B_{h,t}, \tag{72}$$

$$B_{e,t}(i) = \left(\frac{r_t^e(i)}{r_t^e} \right)^{-\theta_t^e} B_{e,t}. \tag{73}$$

Equations (72) and (73) are the demand functions from households and entrepreneurs respectively, and $\theta_t^{IH} > 0$ and $\theta_t^e > 0$ are the elasticities of substitution between household loans and corporate credit from all loan branches. They follow AR(1) processes and can be interpreted as markup shocks to the lending rates for household and business loans, respectively.

The first-order condition for the loan rate to households reads as (suppressing i):

$$1 - \theta_t^{IH} + \theta_t^{IH} \frac{r_t^{b,h}}{r_t^F} - \phi^F \left(\frac{r_t^F}{r_{t-1}^F} - 1 \right) \frac{r_t^F}{r_{t-1}^F} + E_t \left[\Delta_{t+1} \phi^F \left(\frac{r_{t+1}^F}{r_t^F} - 1 \right) \left(\frac{r_{t+1}^F}{r_t^F} \right)^2 \frac{P_{t+1}}{P_t} \frac{B_{h,t+1}}{B_{h,t}} \right] = 0. \tag{74}$$

In the absence of adjustment costs, $\phi^F = 0$, the mortgage loan rate collapses to a markup over the wholesale lending rate (which is again a markup over the money-market rate (see (68))), $r_t^F = \frac{\theta_t^{IH}}{\theta_t^{IH}-1} r_t^{b,h}$. The third term in (74) ensures that the loan branch also takes into account future prices when setting today's price.

In a similar fashion, the first-order condition for the loan rate to entrepreneurs, $r_t^e\left(i\right)$, becomes:

$$1 - \theta_t^e + \theta_t^e \frac{r_t^{b,e}}{r_t^e} - \phi^e \left(\frac{r_t^e}{r_{t-1}^e} - 1\right) \frac{r_t^e}{r_{t-1}^e} + E_t \left[\Delta_{t+1} \phi^e \left(\frac{r_{t+1}^e}{r_t^e} - 1\right) \left(\frac{r_{t+1}^e}{r_t^e}\right)^2 \frac{P_{t+1}}{P_t} \frac{B_{e,t+1}}{B_{e,t}}\right] = 0. \quad (75)$$

D.8.3 The deposit branch

The deposit branch lends to the wholesale branch at money market net rate r_t and pays out interest on household deposits at rate $r_t^d\left(i\right)$. It faces costs when changing the deposit rate, governed by parameter ϕ^D. The maximization problem becomes

$$\max_{\left\{r_t^d(i)\right\}} E_s \sum_{t=s}^{\infty} \Delta_{s,t} \left[r_t D_t\left(i\right) - r_t^d\left(i\right) D_t\left(i\right) - \frac{\phi^D}{2} \left(\frac{r_t^d\left(i\right)}{r_{t-1}^d\left(i\right)} - 1\right)^2 r_t^d D_t\right],$$

subject to deposit demand from households:

$$D_t\left(i\right) = \left(\frac{r_t^d\left(i\right)}{r_t^d}\right)^{\theta_t^D} D_t, \quad (76)$$

where $\theta^D > 0$ is the elasticity of substitution between deposit services.

The first-order condition with respect to $r_t^d\left(i\right)$ becomes:

$$-(1+\theta^D) + \theta^D \frac{r_t}{r_t^d} - \phi^D \left(\frac{r_t^d}{r_{t-1}^d} - 1\right) \frac{r_t^d}{r_{t-1}^d} + E_t \left[\Delta_{t+1} \phi^D \left(\frac{r_{t+1}^d}{r_t^d} - 1\right) \left(\frac{r_{t+1}^d}{r_t^d}\right)^2 \frac{P_{t+1}}{P_t} \frac{D_{t+1}}{D_t}\right] = 0. \quad (77)$$

In the absence of adjustment costs the deposit rate collapses to a mark-down on the money-market rate ($r_t^d = \frac{\theta^D}{1+\theta^D} r_t$).

D.9 Oil sector

To take into account the significance of the oil sector for the Norwegian economy, an explicit oil sector is incorporated in NEMO. The oil sector builds on Bergholt et al. (2019). The sector consists of supply firms as well as a domestic and a foreign extraction firm. The supply firms combine labour, capital and final goods to produce oil supply goods that are used for oil investment by the domestic extraction firm and are exported to a foreign oil extraction firm. The representative domestic oil extraction firm undertakes two activities: (i) it invests in rigs, using solely oil supply goods as inputs, and (ii)) it extracts and exports oil, using rigs and oil in the ground as inputs.

D.9.1 Supply firms

A continuum of oil supply firms, indexed r, combines final goods $Q_{O,t}(r)$ (priced at $P_t^{QO} = P_t$), labour from households $L_{O,t}(r)$ and capital rented from entrepreneurs $\overline{K}_{O,t}(r)$ to produce a good $Y_{R,t}(r)$ that is used for oil investment by an extraction firm and exports to a foreign oil extraction firm. The wage earned by households working in the oil supply sector is $W_{O,t}$, equal to W_t because of perfect labour mobility, while the rental price of utilized capital is $R_{KO,t}$, equal to $R_{K,t}$ due to perfect mobility of capital.

The production function for supply firm r is:

$$Y_{R,t}(r) = Z_R Q_{O,t}^{\alpha_q}(r)(Z_t L_{O,t}(r))^{\alpha_l} \overline{K}_{O,t}^{1-\alpha_q-\alpha_l}(r), \tag{78}$$

where Z_R is oil supply productivity, α_q is the final goods share in production, α_l is the labour share and $1 - \alpha_q - \alpha_l$ is the capital share in production. Including final goods as inputs ensures that imports indirectly enter the production function. Minimizing costs, subject to (78), gives rise to the following conditional demand functions and marginal cost function:

$$Q_{O,t}(r) = \alpha_q \left(\frac{P_t^{QO}}{MC_{R,t}} \right)^{-1} Y_{R,t}(r), \tag{79}$$

$$L_{O,t}(r) = \alpha_l \left(\frac{W_{O,t}}{MC_{R,t}} \right)^{-1} Y_{R,t}(r), \tag{80}$$

$$\overline{K}_{O,t}(r) = (1 - \alpha_q - \alpha_l) \left(\frac{R_{KO,t}}{MC_{R,t}} \right)^{-1} Y_{R,t}(r), \tag{81}$$

$$MC_{R,t} = \frac{1}{Z_R} \left(\frac{P_t^{QO}}{\alpha_q} \right)^{\alpha_q} \left(\frac{W_{O,t}}{\alpha_l} \right)^{\alpha_l} \left(\frac{R_{KO,t}}{1 - \alpha_q - \alpha_l} \right)^{1-\alpha_q-\alpha_l}. \tag{82}$$

Oil supply firms sell their goods under monopolistic competition. Each firm r charges different prices at home and abroad, $P_t^R(r)$ in the domestic market and $P_t^{R^*}(r)$ abroad, where the latter is denoted in foreign currency. Dividends (which are paid out to households) becomes:

$$\Psi_t\left(r\right) = P_t^R\left(r\right) I_{OF,t}(r) + P_t^{R*}\left(r\right) S_t M_{O*,t}(r) - MC_{R,t} Y_{R,t}(r), \tag{83}$$

where $I_{OF,t}(r)$ are goods delivered to the domestic extraction firm, $M_{O,t}^*(r)$ are supply goods for exports and S_t is the nominal exchange rate. Total production of supply goods must satisfy: $Y_{R,t} = I_{OF,t}(r) + M_{O*,t}(r)$.

It can be shown that supply firm r faces the following demand functions from the domestic and foreign extraction sectors, respectively:

$$I_{OF,t}(r) = \left(\frac{P_t^R\left(r\right)}{P_t^R}\right)^{-\theta^R} I_{OF,t}, \tag{84}$$

$$M_{O*,t}(r) = \left(\frac{P_t^{R*}\left(r\right)}{P_t^{R*}}\right)^{-\theta^{R^*}} M_{O*,t}, \tag{85}$$

where θ^R and θ^{R^*} are the elasticities of substitution between goods in the two markets respectively. Additionally, the costs of adjusting prices in the domestic and the foreign markets are given by:

$$\gamma_{PR,t}(r) \equiv \frac{\phi^{PR}}{2}\left[\frac{P_t^R\left(r\right)/P_{t-1}^R\left(r\right)}{P_{t-1}^R/P_{t-2}^R} - 1\right]^2, \tag{86}$$

$$\gamma_{PR^*,t}(r) \equiv \frac{\phi^{PR^*}}{2}\left[\frac{P_t^{R^*}\left(r\right)/P_{t-1}^{R^*}\left(r\right)}{P_{t-1}^{R^*}/P_{t-2}^{R^*}} - 1\right]^2, \tag{87}$$

respectively, where ϕ^{PR} and ϕ^{PR^*} govern the costs of adjusting prices.

Profit maximisation with respect to P_t^R and $P_t^{R^*}$ leads to the following first-order conditions in symmetric equilibrium (index r removed), respectively:

$$\begin{aligned} &I_{OF,t} - \theta^R I_{OF,t} + MC_{R,t}\theta^R \frac{I_{OF,t}}{P_t^R} - \phi^{PR}\left[\frac{P_t^R/P_{t-1}^R}{P_{t-1}^R/P_{t-2}^R} - 1\right]\frac{P_t^R/P_{t-1}^R}{P_{t-1}^R/P_{t-2}^R} I_{OF,t} \\ &+E_t\left\{\Delta_{t+1}\phi^{PR}\left[\frac{P_{t+1}^R/P_t^R}{P_t^R/P_{t-1}^R} - 1\right]\frac{(P_{t+1}^R/P_t^R)^2}{P_t^R/P_{t-1}^R} I_{OF,t+1}\right\} = 0, \end{aligned} \tag{88}$$

$$S_t M_{O*,t} - \theta^{R^*} S_t M_{O*,t} + MC_{R,t}\theta^{R^*} \frac{M_{O*,t}}{P_t^{R^*}} - \phi^{PR^*} \left[\frac{P_t^{R^*}/P_{t-1}^{R^*}}{P_{t-1}^{R^*}/P_{t-2}^{R^*}} - 1 \right] \frac{P_t^{R^*}/P_{t-1}^{R^*}}{P_{t-1}^{R^*}/P_{t-2}^{R^*}} S_t M_{O*,t}$$
$$+E_t \left\{ \Delta_{t+1}\phi^{PR^*} \left[\frac{P_{t+1}^{R^*}/P_t^{R^*}}{P_t^{R^*}/P_{t-1}^{R^*}} - 1 \right] \frac{\left(P_{t+1}^{R^*}/P_t^{R^*}\right)^2}{P_t^{R^*}/P_{t-1}^{R^*}} S_{t+1} M_{O*,t+1} \right\} = 0. \quad (89)$$

Because of the adjustment costs, the supply firms take into account the full future path of expected prices when setting current prices. In the case without any adjustment costs, prices would be set as markups over marginal costs in every period: $P_t^R = \frac{\theta^R}{\theta^R - 1} MC_{R,t}$ and $P_t^{R^*} = \frac{\theta^{R^*}}{\theta^{R^*}-1}\frac{1}{S_t} MC_{R,t}$.

D.9.2 The domestic extraction firm

Domestic oil extraction ($Y_{O,t}$) requires oil reserves (O_t) and oil rig services ($\overline{F}_{O,t}$) so that

$$Y_{O,t} = Z_O \overline{F}_{O,t}^{\alpha_o} O_t^{1-\alpha_o}, \quad (90)$$

where Z_O is oil extraction productivity and α_o is the rigs share. As we abstract from issues of depletion and discovery of new oil fields, O_t is treated as a parameter, $O_t = O$. Hence, $\alpha_o \in [0,1)$ implies decreasing returns to scale. Effective oil rig services are determined by oil rig capacity, $F_{O,t-1}$, and a utilisation rate of that capacity, $U_{F,t}$:

$$\overline{F}_{O,t} = F_{O,t-1} U_{F,t}. \quad (91)$$

In (91) it is assumed that the rig capacity for period t is set in period $t-1$. Hence, to increase effective oil production in period t, the oil extraction firm must increase the utilisation rate, which comes at a cost. Due to this endogenous utilisation rate, there will be a tradeoff between raising the utilisation rate to increase production in the current period, or to increase investment that will increase production capacity in future periods. The unit cost of increasing the utilisation rate in terms of oil supply goods is represented by the function $a(U_{F,t})$:

$$a(U_{F,t}) = \gamma^O (U_{F,t} - 1) + \frac{\gamma^O \phi^{uf}}{2} (U_{F,t} - 1)^2. \quad (92)$$

The cost of changing the utilisation rate is governed by the parameters γ^O and ϕ^{uf}.[22] The extraction firm can invest in rig capacity, using oil supply goods as the investment good. Hence, the dynamics of oil rig capacity is characterised by:

$$F_{O,t} = (1-\delta_O)F_{O,t-1} + Z_{IOIL,t}\left[1 - \Psi_O\left(\frac{I_{O,t}}{I_{O,t-1}}\right)\right] I_{O,t}, \tag{93}$$

where δ_O is the rigs depreciation rate and $\Psi_O(\frac{I_{O,t}}{I_{O,t-1}}) = \frac{\phi^{RI}}{2}(\frac{I_{O,t}}{I_{O,t-1}} - \pi^z_t)^2$ represents the costs of changing investment levels, governed by the parameter ϕ^{RI}. The parameter π^z_t is the growth rate of the economy and $Z_{IOIL,t}$ is an oil-specific technology shock, that follows an AR(1) process. A positive innovation leads to more operative oil rigs in future periods for any given level of investment activity in the current period. Total demand for supply goods from the domestic extraction firms is given by the sum of gross investments and the cost associated with the utilisation rate of rigs: $I_{OF,t} = I_{O,t} + a(U_{F,t})F_{O,t-1}$.

Oil production is given by $Y_{O,t}$, which is exported at a price P^{O*}_t in foreign currency. Consequently, the oil price in domestic currency is given by $S_t P^{O*}_t$, where S_t is the nominal exchange rate. The extraction firm maximises the discounted expected stream of cash flows, subject to extraction technology and rig accumulation:

$$\max_{\{F_{O,t}, I_{O,t}, U_{F,t}\}} \sum_{t=s}^{\infty} \Delta_{s,t}\left[S_t P^{O*}_t Y_{O,t} - P^R_t I_{OF,t}\right], \tag{94}$$

where $\Delta_{s,t}$ is the stochastic discount factor between period s and t.

The intertemporal first-order conditions with respect to $F_{O,t}$ and $I_{O,t}$ become:[23]

$$\Omega_{O,t} = E\Big[\Delta_{t+1}\Big(\alpha_o S_{t+1} P^{O*}_{t+1} Y_{O,t+1} F^{-1}_{O,t} - P^R_{t+1} a(U_{F,t+1}) + (1-\delta_O)\Omega_{O,t+1}\Big)\Big], \tag{95}$$

$$\begin{aligned} P^R_t = \Omega_{O,t} Z_{IOIL,t}&\left[1 - \Psi'_O\left(\frac{I_{O,t}}{I_{O,t-1}}\right)\frac{I_{O,t}}{I_{O,t-1}} - \Psi_O\left(\frac{I_{O,t}}{I_{O,t-1}}\right)\right] \\ +E&\left[\Delta\Omega_{O,t+1} Z_{IOIL,t+1}\Psi'_O\left(\frac{I_{O,t+1}}{I_{O,t}}\right)\left(\frac{I_{O,t+1}}{I_{O,t}}\right)^2\right]. \end{aligned} \tag{96}$$

[22] By using $U_{F,ss} = 1$, it can easily be shown that $\gamma^O = a'(U_{F,ss})$. Kravik et al. (n.d.) show in their steady-state solution (by combining steady-state versions of equation (95) and (97)) that $\gamma^O = a'(U_{F,ss}) = (\delta_O + \frac{\pi^z_{ss}}{\beta} - 1)$.

[23] These are identical to equation (8) and (9) in Bergholt et al. (2019).

Equation (95) determines the present marginal value of oil rig capacity, $\Omega_{O,t}$ (the shadow price of rig capacity). The first term on the right-hand side is the net income from installing more rigs at the margin. The second term is the utilisation cost associated with more rigs, while the third term represents the net-of-depreciation continuation value.

Equation (96) aligns the marginal cost of new investment (P_t^R) with the marginal gain from increased rig capacity. The first term on the right is the marginal gain from more capacity, net of adjustment costs. The second term reflects that more investment in period t reduces the need for costly investment adjustments in the future. The optimality conditions imply the oil company bases its investment decisions on the entire expected future oil price path.

The first-order condition with respect to the utilisation rate $U_{F,t}$ becomes:

$$\alpha_o S_t P_t^{O*} \frac{Y_{O,t}}{U_{F,t}} = P_t^R a'(U_{F,t}) F_{O,t-1}. \tag{97}$$

In the optimum case, the marginal revenues from a higher rig utilisation rate is equated to the marginal utilisation costs.

D.9.3 The foreign extraction firm

The foreign extraction firm is modelled in a simpler fashion. It extracts oil, $Y_{O*,t}$, invests, $I_{O*,t}$, and imports oil supply goods from the home country's oil supply sector, $M_{O*,t}$, with the following production function:[24]

$$Y_{O*,t} = M_{O*,t}^{\alpha_{o*}} I_{O*,t}^{\alpha_{io*}} (O_*)^{1-\alpha_{io*}-\alpha_{o*}}. \tag{98}$$

O_* is oil in the ground abroad, set to a constant and α_{o*} is the share of domestically produced oil supply goods used as inputs. Maximising profits leads to the following demand function for oil supply goods from abroad:

$$M_{O*,t} = \alpha_{o*} \left(\frac{P_t^{R*}}{P_t^{O*}} \right)^{-1} Y_{O*,t}. \tag{99}$$

Note that $Y_{O*,t}$ follows an AR(1) process and can be interpreted as a foreign oil production shock in the model (making $I_{O*,t}$, O_* and α_{io*} superfluous and not determined).

[24] One can think of the product $M_{O*,t}^{\alpha_{o*}} I_{O*,t}^{\alpha_{io*}}$ as the foreign rigs production function, corresponding to $\overline{F}_{O,t}^{\alpha_o}$ in (90).

D.9.4 The GPFG

In Norway, the Government Pension Fund Act stipulates that the government's cash flow from the petroleum industry shall be transferred to the GPFG. A fiscal rule specifies that the transfers from the GPFG to the central government's fiscal budget shall follow the expected real return on the GPFG over time. In NEMO, this relationship is simplified, as the GPFG and fiscal policy are independently treated. The full sales revenue is transferred to the GPFG in every period. Hence, the GPFG, $B_{F,t}$, accumulates according to:

$$B_{F,t} = (1 - \rho_{G_F}) \left[R^*_{t-1} \frac{P_{t-1}}{P_t} \frac{S_t}{S_{t-1}} B_{F,t-1} \right] + S_t \frac{P^{O*}_t}{P_t} Y_{O,t}, \tag{100}$$

where the amount (in real terms) transferred from the GPFG is given by:

$$G_{F,t} = \rho_{G_F} \left[R^*_{t-1} \frac{P_{t-1}}{P_t} \frac{S_t}{S_{t-1}} B_{F,t-1} \right]. \tag{101}$$

The transfer, $G_{F,t}$, ensures that the GPFG, $B_{F,t}$ is stationary. For instance, following an oil price shock, the fund will never return back to its steady state when $\rho_{G_F} = 0$.

In the model, we assume that the transfer from the fund goes to the banking sector (and not to the government sector). This assumption is deemed necessary to be able to replicate (in the steady state of the model) the fact that mainland Norway has positive net imports as well as a negative (private) asset position (held by the banking sector) (see Section D.12 for the mainland debt accumulation equation (B^*_t) and further details).

D.10 Foreign sector

The foreign sector in NEMO is split into two parts. The first part derives the optimality condition for the price setting of the imported good that enters into the final good sector as well as export demand for the domestic intermediate good. The second part, starting with (104) below, is a block exogenous system of equations based on a standard New Keynesian model that links foreign output, foreign money market rates, foreign inflation and the international oil price. We adopt the small open economy assumption, implying that the foreign economy (rest of the world) is fully exogenous from the point of view of the Norwegian economy. Hence, economic developments in Norway have no effects on its trading partners. The two parts are linked since export demand depends on trading partners' output level.

The intermediate sector abroad is assumed to be symmetric to the domestic intermediate sector. Foreign exporters enjoy market power and face price adjustment costs. The optimal price setting rule for the imported price P_t^M in domestic currency (that enters into the domestic final good sector as inputs) will therefore be (cf. (42)):

$$\begin{aligned} M_t - \theta^F M_t + S_t MC_t^* \theta^F \frac{M_t}{P_t^M} - \phi^{PM} \left[\frac{\pi_t^M}{\pi_{t-1}^M} - 1 \right] \frac{\pi_t^M}{\pi_{t-1}^M} M_t \\ + E_t \left\{ \Delta_{t+1}^* \phi^{PM} \left[\frac{\pi_{t+1}^M}{\pi_t^M} - 1 \right] \frac{(\pi_{t+1}^M)^2}{\pi_t^M} M_{t+1} \frac{S_t}{S_{t+1}} \right\} = 0, \end{aligned} \quad (102)$$

where Δ_{t+1}^* is the foreign stochastic discount factor (assumed equal to $(R_t^*)^{-1}$ for simplicity), ϕ^{PM} is a parameter that captures the cost of changing the price of imported goods, MC_t^* denotes foreign marginal costs that follow a shock process and θ^F is the substitution elasticity between imported goods. Note that we have defined $\pi_t^M \equiv P_t^M / P_{t-1}^M$. In the absence of adjustment costs, $\phi^{PM} = 0$, prices would simply be set as a markup over marginal costs in every period $P_t^M = \frac{\theta^F}{\theta^F - 1} S_t MC_t^*$ with full exchange rate pass-through.

Turning to exports, the export demand for the intermediate good is given by (symmetric to (45)):

$$M_t^* = (1 - \nu_t^*) \left(\frac{P_t^{M*}}{P_t^*} \right)^{-\mu^*} Y_{NAT,t}^*, \quad (103)$$

where ν_t^* follows an AR(1) process and can be interpreted as an export demand shock. $Y_{NAT,t}^*$ is output abroad.

The second part of the foreign sector is modelled as a block-exogenous set of equations, linking the foreign inflation gap, the foreign output gap, the foreign interest rate gap and the oil price gap.[25] Moreover, the foreign sector is divided into two groups: trading partners and non-trading partners. The former is a group of Norway's largest export and import partners; the latter is the foreign sector minus trading partners. The model for the foreign sector is based on a standard New Keynesian model, with a dynamic IS curve representing the relationship between output and the real interest rate and a Phillips curve linking inflation to output, both with added backward-looking terms to add more dynamics and realism.

[25] In the rest of this section, all variables are in gap form (deviation from steady state). The gap indicator $\widehat{\ }$ is suppressed for readability.

The oil price has been added to the system of equations to negatively affect trading partners' output and positively affect their rate of inflation. A rise in global demand will increase international oil prices, but oil prices can also increase due to reduced international supply. The effects of a demand-driven change in the oil price are stronger on the Norwegian economy than the effects of a supply-driven change, since the latter weakens exports from the domestic non-oil sector, dampening the positive effect on GDP. The effects of oil prices on the Norwegian economy are further discussed in Gerdrup et al. (2017b).

Output for trading partners is given by equation (104) and (105), the latter being the traditional IS curve (with the parameter ψ^{R*} relating the real interest rate to output):

$$Y^*_{NAT,t} = \phi^{Y*} Y^*_{NAT,t-1} + (1 - \phi^{Y*}) Y^*_{FNAT,t} - \phi^{O*} P^{O*}_t + \phi^{YNTP*} Y^{NTP}_{NAT,t} + z_{U*,t}, \tag{104}$$

where $Y^*_{FNAT,t}$ is defined as:

$$Y^*_{FNAT,t} = Y^*_{FNAT,t+1} - \psi^{R*}(R^*_t - \pi^*_{t+1}). \tag{105}$$

Trading partners' output is affected negatively by the oil price gap, P^{O*}_t, as Norway's trading partners are net oil importers, and positively by the output gap among non-trading partners, $Y^{NTP}_{NAT,t}$. ϕ^{O*} and ϕ^{YNTP*} are positive parameters. ϕ^{Y*} is the lag operator, and $z_{U*,t}$ follows an AR(1) process and can be interpreted as a trading partner demand shock.

The output gap for non-trading partners, $Y^{NTP}_{NAT,t}$, is assumed to follow:

$$Y^{NTP}_{NAT,t} = \lambda^{YNTP} Y^{YNTP}_{NAT,t-1} - \phi^{ONTP} P^{O*}_t + \phi^{YNTP} Y^*_{NAT,t} + z_{YNTP,t}, \tag{106}$$

where $z_{YNTP,t}$ can be interpreted as a global demand shock (equal to its innovation as there is no corresponding persistence parameter), and λ^{YNTP}, ϕ^{ONTP} and ϕ^{YNTP} are parameters. Total global output is given by a weighted sum of trading partners' and non-trading partners' output:

$$Y^{GLOB}_{NAT,t} = \alpha^{GLOB} Y^*_{NAT,t} + (1 - \alpha^{GLOB}) Y^{NTP}_{NAT,t}, \tag{107}$$

where α^{GLOB} is the trading partners' output share of total global output.

Inflation for trading partners is given by equations (108) and (109), the latter being the traditional

Phillips curve:

$$\pi_t^* = \phi^{P*}\pi_{t-1}^* + (1-\phi^{P*})\pi_{F,t}^* + \phi^{OP*}P_t^{O*}, \tag{108}$$

where $\pi_{F,t}^*$ is defined as:

$$\pi_{F,t}^* = \alpha^{P*}\pi_{F,t+1}^* + \alpha^{Y*}Y_{NAT,t}^* + z_{\theta^{H*},t}. \tag{109}$$

α^{Y*} is the traditional Phillips curve parameter, whereas ϕ^{OP*} is a positive parameter picking up the positive effect of real oil prices on marginal costs for trading partner firms. ϕ^{P*} is the lag operator and $z_{\theta^{H*},t}$ is a foreign price markup shock following an AR(1) process.

The oil price is forward-looking and assumed positively affected by global demand:

$$P_t^{O*} = \beta^O P_{t+1}^{O*} + \kappa^O Y_{NAT,t}^{GLOB} + z_{PO*,t}, \tag{110}$$

where $z_{PO*,t}$ can be interpreted as an international oil supply shock, following an AR(1) process, and β^O and κ^O are parameters.

Lastly, the foreign monetary policy rate (equal to the foreign money market rate) is given by a simple policy rule with smoothing:

$$R_t^* = \omega^{R*}R_{t-1}^* + (1-\omega^{R*})\left[\omega^{P*}\pi_t^* + \omega^{Y*}Y_{NAT,t}^*\right] + z_{R*,t}, \tag{111}$$

where $z_{R*,t}$ follows an AR(1) process and can be interpreted as a trading partner monetary policy shock, the parameter ω^{R*} governs interest rate smoothing, and ω^{P*} and ω^{Y*} are weights on inflation and output, respectively.

D.11 Market clearing conditions

The following set of equilibrium conditions needs to hold in order to close the model. In the intermediate goods market, total production needs to equal goods for domestic use and exports:

$$T_t = Q_t + M_t^*. \tag{112}$$

Total production of final goods needs to equal the sum of the following demand components: Consumption, investment, housing investment, government expenditure and inputs into the oil supply sector:

$$A_t = C_t \ + I_{C,t} + I_{H,t} + G_t + Q_{O,t}. \tag{113}$$

Total investments must equal the sum of business and housing investment (note that it does note include oil supply investment):

$$I_t = I_{C,t} + I_{H,t}. \tag{114}$$

Total production of capital goods must equal capital usage in the oil and traditional sector combined:

$$\overline{K}_t = \overline{K}_{O,t} \ + \overline{K}_{I,t}. \tag{115}$$

Equilibrium in the labour market is characterised by:

$$L_t = L_{O,t} \ + L_{I,t}. \tag{116}$$

For the oil supply firms, total production must equal use by the domestic extraction firm and oil supply exports.

$$Y_{R,t} = I_{OF,t} + M_{O*,t}. \tag{117}$$

Lastly, we define output for mainland Norway as:

$$Y_{NAT,t} = (C_t + G_t + I_t + P_t^R I_{O,t} + S_t P_t^{M*} M_t^* + S_t P_t^{R*} M_{O*,t} - P_t^M M_t) \frac{1}{\log(z_{x,t})}, \tag{118}$$

where the first four terms on the right hand side are household and government consumption, investment and oil supply investment, respectively. The following two terms are traditional and oil supply exports and $P_t^M M_t$ represents imports. Finally, $z_{x,t}$ is an inventory shock to the mainland economy that follows an AR(1) process. Total output is given by:

$$Y_{NAT,t}^{TOTAL} = Y_{NAT,t} + S_t P_t^{O*} Y_{O,t}^*, \tag{119}$$

i.e. mainland output plus production from oil extraction (which is exported).

D.12 Resource constraints, UIP and the current account

The division of the Norwegian economy into a mainland share and a non-mainland share entails that foreign debt for the country as a whole is equal to mainland private foreign debt (held by banks) less government claims:

$$B_t^{TOT*} = B_t^* - B_{F,t}. \tag{120}$$

Taking the household budget constraint as the point of departure and inserting for profits, dividends and lump-sum taxes, it is possible to derive mainland Norway's resource constraint, i.e. the private foreign debt accumulation equation, as:

$$B_t^* = \frac{P_{t-1}}{P_t} R_{t-1} B_{t-1}^* + \left[\frac{P_t^M}{P_t} M_t - S_t \frac{P_t^{R*}}{P_t} M_{O*,t} - S_t \frac{P_t^{M*}}{P_t} M_t^* - \frac{P_t^R}{P_t} I_{OF,t} - G_{F,t} \right], \tag{121}$$

where the bracketed term is the current account for mainland Norway, i.e. positive net imports imply increased external debt for mainland Norway. The first term in the brackets is imports, the second term is oil supply exports, the third term is traditional exports and the fourth term is "exports" of oil supply goods from mainland Norway to non-mainland Norway.[26] The fifth term, $G_{F,t}$, represents transfers from the GPFG to the mainland economy.

The accumulation equation for government claims and the size of transfers ($G_{F,t}$) were derived in Section D.9.4. Note that $G_{F,t}$ is included both in B_t^* and $B_{F,t}$ and hence cancels out (except for the interest rate differential (see equation (100))). In reality, the annual transfers from the GPFG go to the government. As this mechanism is not modelled in NEMO and we do not wish transfers from the GPFG to drive banking sector net worth, we set $G_{F,t}$ to its steady-state value in (121) when we operate the model.

The uncovered interest rate parity was derived in Section D.8.1 and is repeated here:

$$E_t \left[\left[1 - \gamma_t^{B^*} \right] R_t^* \frac{S_{t+1}}{S_t} \right] = R_t. \tag{122}$$

In (122), $1 - \gamma_t^{B^*}$ is the debt-elastic risk premium, R_t^* is the foreign money market rate and S_t is the nominal exchange rate (NOK per foreign currency unit). It is assumed that the risk premium depends positively on the country's net foreign debt position (B_t^{TOT*}) and the anticipated growth rate of the exchange rate:[27]

$$1 - \gamma_t^{B^*} = exp\Big[\phi^B (B_t^{TOT*} - B_{ss}^{TOT*}) - \phi^S (E_t S_{t+1} S_t - S_{ss}^2) \Big] + z_t^B, \tag{123}$$

[26] The latter term is ignored in the model file, in accordance with the national accounts.

[27] Technically, the risk premium is defined in terms of stationary variables. Hence, in equation (123) the B_t^{TOT*} refers to the stationary version and S_t is the *real* exchange rate.

where z_t^B is an exogenous exchange rate risk premium shock following an AR(1) process and ϕ^B and ϕ^S are non-negative parameters.

The assumption of a financial friction is necessary to ensure stationarity in small open economy models like NEMO. Augmenting the risk premium with the anticipated growth rate of the exchange rate tend to give a more hump-shaped exchange rate response following a risk premium shock (see Adolfson et al. (2013) for a discussion).[28]

The relationship between the net foreign asset position, the risk premium and the UIP is summarised in Figure 62.

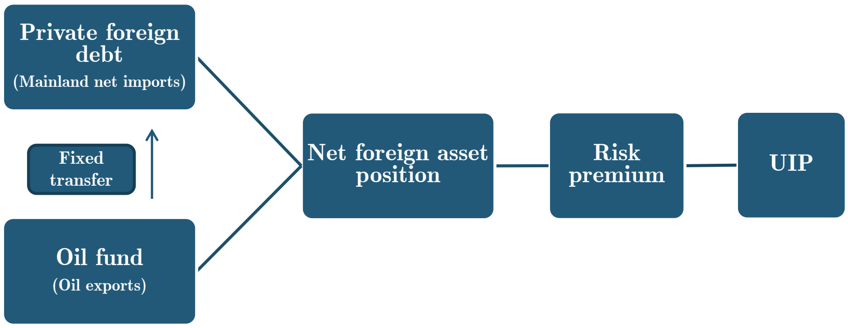

Figure 62: The relationship between the net foreign asset position, the risk premium and the UIP in NEMO.

D.13 Monetary policy

The central bank controls the policy rate ($R_{P,t}$), equal to the money market rate divided by the exogenous money market risk premium ($R_t = R_{P,t}Z_{prem,t}$), where $Z_{prem,t}$ is the risk premium and a shock (following an AR(1) process). The central bank conducts optimal monetary policy, i.e. setting the interest rate to minimise a loss function. The loss function consists of the discounted (weighted) sum of future expected quadratic deviations from steady-state values of inflation, output, the level of the policy rate and changes in the policy rate. More specifically, the central bank minimises the following loss function, using the policy rate as instrument (either under commitment or discretionary policies), where $\widehat{x}_t$ denotes variable x's log-deviation from the steady state:

$$\min_{\{\widehat{R}_{P,t}\}} \sum_{t=s}^{\infty} \beta_p^{t-s} \left[(\widehat{\pi}_{pol,t})^2 + \lambda_y \left(\widehat{Y}_{NAT,t} \right)^2 + \lambda_{dr} \left(\triangle R_{P,t} \right)^2 + \lambda_{lr} \left(\widehat{R}_{P,t}^{YEAR} \right)^2 \right], \tag{124}$$

[28] ϕ^S is weakly identified in the model and set to 0.

where β_p is the central bank's discount factor, $\widehat{R}_{P,t}$ is the policy rate gap, $\widehat{Y}_{NAT,t}$ is the mainland output gap (defined in Section D.11), $\widehat{\pi}_{pol,t}$ is four quarter consumer price inflation as a deviation from the inflation target, $\triangle R_{P,t}$ is the annualised change in the policy rate and $\widehat{R}_{P,t}^{YEAR}$ is the annualised policy rate gap. The definitions of the three latter variables are:

$$\widehat{\pi}_{pol,t} = \widehat{\pi}_t + \widehat{\pi}_{t-1} + \widehat{\pi}_{t-2} + \widehat{\pi}_{t-3} + \log\left(\frac{z_{inf,t}}{z_{inf,ss}}\right), \tag{125}$$

$$\triangle R_{P,t} = 4\left(R_{P,t} - R_{P,t-1}\right), \tag{126}$$

$$\widehat{R}_{P,t}^{YEAR} = 4\widehat{R}_{P,t}. \tag{127}$$

where $z_{inf,t}$ is a shock to the inflation target that follows an AR(1) process, which can be interpreted as a monetary policy shock. λ_y, λ_{dr} and λ_{lr} are the corresponding weights in the loss function.

Monetary policy in NEMO can alternatively be solved under a Taylor type rule of the following kind:

$$\widehat{R}_t = \omega_R \widehat{R}_{t-1} + (1-\omega_R)(\omega_P \widehat{\pi}_t + \omega_Y \widehat{Y}_{NAT,t}) + Z_{RN3M,t}, \tag{128}$$

where R_t is the money market rate, ω_R governs interest rate persistence and ω_P and ω_Y are the weights on inflation and output respectively, while $Z_{RN3M,t}$ represents a monetary policy shock that follows an AR(1) process.

E Calibration and estimation of NEMO

E.1 Calibration of the steady state

The steady-state solution of the model is derived recursively and is publicly available in Kravik et al. (n.d.). We calibrate the steady state of the model by matching real and financial great ratios. Specifically, we aim at matching 14 macroeconomic aggregates and 12 financial targets. Our sample period is 2010-2016. Table 6 lists the empirical ratios and the model's steady-state counterparts.

Reflecting the assumption of a small open economy, the nominal interest rate in Norway in the steady state is determined by the foreign sector and the inflation target in Norway. We set both the inflation target and the nominal policy rate to 2% on an annual basis in the domestic economy and abroad, implying a real policy rate of 0%. This is in line with data over the sample period for Norway. The low nominal policy rate is important to reflect the implications of the ELB in the model experiments. The money market premium is set to 0.5% on an annual basis in Norway and abroad. The money market rate is therefore 2.5%. Parameters determining interest rate markups are set to match market spreads from the data, i.e. 2.37%, 2.12%, and 0.5% for the business credit spread, the mortgage credit spread and money market-deposit rate spread, respectively on an annual basis. The foreign sector and Norway are assumed to share a steady-state productivity growth rate of 1% on annual basis, which is in line with recent estimates for the Norwegian economy.

We treat the final good as the model's numerator good and accordingly set the price of this good to 1. The price of the intermediate good and the import good are also set to 1 in the steady state. Although markups internationally have shown an increasing trend (Diez et al., 2018), we set markups for the domestic good, the imported good and the exported good to 1.2, following the standard calibration in the literature. In order to match the observed capital-to-mainland gross domestic product (MGDP) ratio of 1.66, we set the capital share parameter, α, to 0.256 and the elasticity of substitution between capital and labour, ξ, to 0.929. This gives a labour income share of about 67% both for the intermediate goods sector and for the total mainland economy in the steady state. This is on the lower side of what is found in the data of around 70 to 75% for Norway.

The elasticity of substitution for labour services, ψ, can be interpreted as the inverse of the degree of market power of the workers (or unions) in the wage-setting process, and reflects the deviation from free competition in the labour market. A relatively high union coverage ratio in Norway implies a low number, whereas low structural unemployment suggest the opposite. We set $\psi = 2.5$, which is on the lower side of empirical estimates. We set ζ, the inverse of the Frisch elasticity of labour supply, to 3, which implies a Frisch elasticity of 0.33.

Because of its large petroleum revenues, Norway has since the mid-1990s accumulated a sovereign wealth fund of more than 2.5 times MGDP. However, combining net positive exports with a positive net foreign asset position in the steady state would violate the transversality condition. To circumvent this, we fix the net foreign asset position, and thus net exports, to zero in the steady state. We reach these targets partly by reducing the target for oil exports-to-MGDP ratio from the empirical observation of around 20% to 16% and partly by increasing the corresponding import share from 34 to 39%.[29] To match export and import ratios, we set the domestic share parameter, ν_{ss}, and the export share parameter, ν^*_{ss}, to 0.65 and 0.21 respectively.[30]

Continuing with the oil sector, we set the factor share parameters in the oil supply production function to match this sector's labour share of total labour and its capital-to-MGDP ratio. We fix the labour share parameter, α_l, to 0.28 and the final goods share parameter, α_q, to 0.69, giving a labour share in the oil sector to total labour of 5.3% and a capital-to-MGDP ratio of 4%. These numbers are somewhat on the lower side of the empirical counterparts of 7% and 4.2%, respectively. This is partly due to the fact that the oil extraction sector is lower in our steady state than in the calibration target period, reflecting the need for a zero trade balance in steady state, as discussed above.

Regarding markups and elasticities in the oil supply sector, we fix the rig depreciation rate (δ_O), the rig share parameter in oil extraction (α_o), the substitution elasticities of supply goods (θ^R and θ^{R^*}) and the size of the oil reserves (O, which enters as a factor of production for the domestic oil extraction company) in order to match the size of the oil production industry, oil supply goods used for oil investment, oil supply exports and capital in the oil extraction sector to MGDP. Due to the lower oil extraction share in the steady state compared to data, the

[29] The oil production share (import share) has shown a decreasing (increasing) trend over time.

[30] A zero net foreign asset position in the steady state also eliminates large wealth effects from interest rate shocks through the risk premium in the UIP condition.

sub-targets also become a little lower than their empirical counterparts.

Turning to the banking sector, we use the regulatory capital risk weights of 0.4 and 0.8 on household and corporate loans, respectively. In accordance with Norwegian financial regulations, we set capital requirements for banks to 15.6%, of which 2% is the countercyclical capital buffer. The internal rates of the banking sector are determined by the linear cost parameter χ_o. We calibrate this and the dividend parameter δ^b to jointly achieve the empirical observation of a return on equity in the Norwegian banking sector at around 10%. Households' principal repayments are assumed to follow from an approximated annuity loan repayment formula (see equation (20) in Appendix D.2). The amortisation rate dynamics parameters α^h and κ^h are set in order to capture the repayment schedule of a 30-year mortgage contract, in line with Norwegian household mortgage data. We set the collateral constraint parameter, ϕ_{ss}, to match a household debt-to-MGDP ratio of 105%. This gives an average loan-to-value (LTV) ratio for households of 84.5% in the model, which is broadly consistent with a 15% downpayment requirement in Norway. For corporate credit demand, we assume that loans are rolled over in every period ($\alpha_e = 0$).

To match the corporate credit-to-MGDP ratio at 85%, we set the entrepreneurial collateral constraint parameter, ϕ_{ss}^{ent}, to 0.9917 in steady state, giving a loan-to-value rate for the entrepreneurs at around 50%. We use the household deposit preference parameter, z^d, to match the deposit ratio.

House prices have over time grown more rapidly than other prices in Norway. We capture this by assuming a negative technology trend growth in housing production of 3.4% annually, matching the observed real house price growth rate of 1.046 annually.

The quarterly capital depreciation rate, δ, is set to 0.0108 in order to match the business investment-to-MGDP ratio of 9%. We set the housing depreciation rate, δ_H, to target the housing stock-to-MGDP ratio of about 124%. This gives a housing investment-to-MGDP ratio of 7% – the empirical target being 6.15%.

Table 6 lists the empirical ratios (averages over the period 2010-2016) and the model's steady-state counterparts.

Table 6: Data targets and steady-state calibration values

Target	Data[a]	Steady state
Macroeconomic aggregates		
Consumption to MGDP	0.51	0.52
Corporate investment toMGDP	0.09	0.09
Housing investment to MGDP	0.06	0.07
Oil investment to MGDP	0.08	0.06
Government spending to MGDP	0.34	0.34
Traditional exports to MGDP	0.16	0.16
Oil supply exports to MGDP	0.07	0.07
Imports to MGDP	0.34	0.39
Physical capital to MGDP	1.66	1.66
Physical capital in oil supply sector to MGDP	0.04	0.04
Physical capital in oil extraction sector to MGDP	0.42	0.28
Housing capital to MGDP	1.24	1.25
Labour in oil sector to total labour	0.07	0.05
Oil production to MGDP	0.20	0.16
Financial sector		
Household lending to total assets	0.55	0.56
Corporate lending to total assets	0.45	0.44
Household deposits to total assets	0.51	0.49
Foreign funding to total assets	0.42	0.42
Bank capital to total assets	0.07	0.09
Total assets to MGDP	1.90	1.90
Bank capital to risk-weighted assets	0.16	0.16
Real return on bank equity	0.10	0.10
Average business credit spread (%)	2.37	2.37
Average mortgage credit spread (%)	2.12	2.12
Average money market-deposit rate spread (%)	0.5	0.5
Average money market premium (%)	0.5	0.5

[a] Averages over the period 2010-2016.

E.2 Estimation of dynamic parameters

We estimate the parameters of NEMO using Bayesian techniques, as outlined in An and Schorfheide (2007). Computations are done using the *RISE* toolbox[31] and *NB Toolbox.*[32]. In this chapter we describe the data used for the estimation, give an account of how the model's steady state is calibrated and report on our prior and posterior distributions.

[31] Rationality In Switching Environments (*RISE*) is an object-oriented Matlab toolbox for solving and estimating nonlinear Regime-Switching DSGE models. The toolbox was developed by Junior Maih and is freely available for downloading at https://github.com/jmaih/RISE_toolbox.

[32]NB Toolbox has been developed within Norges Bank and will be released for public use in the future.

E.3 Data

The data set used for estimation of NEMO is quarterly and runs from 2001Q1, the year Norges Bank officially introduced (flexible) inflation targeting, to 2017Q4. The macroeconomic time series cover Norwegian and international variables. Real domestic variables include GDP, consumption, exports, imports, government expenditure, investment and hours worked. Financial variables include household and corporate credit. Price variables include wages, consumer prices, house prices, lending rates to households, lending rates to corporations, money market interest rates and the policy rate. Lastly, international variables include the exchange rate, the international oil price and foreign GDP, money market rates and inflation. The data sources include Statistics Norway, Norges Bank's own calculations, and international sources, particularly the IMF and Thomson Reuters. The data for the real variables are at constant prices from the national accounts, whereas credit and house prices are deflated by consumer prices. In total, there are 26 observable variables used in the estimation of NEMO.

E.3.1 Data transformation and the steady state

NEMO is linearised around a steady state when solved. As with most DSGE models, NEMO assumes that the economy has one balanced-growth path and that the different demand components of GDP grow at the same pace over time.[33] There is also a close relationship between the steady-state real interest rate and the balanced-growth path. However, actual data are not as well-behaved. Different variables exhibit different trends within the time span we have available, but we have to choose only one set of steady-state values that are both deemed relevant for the recent past and the economy going forward and that in addition are model-consistent.

Even though business cycle dynamics can be influenced by the calculated gradients around the steady state, most of the business cycles dynamics are determined by the dynamic parameters and shock processes in the model. Consequently, since the model is too simple to explain multiple, time-varying trends in the data, we use pre-filtered gap series (i.e. log-deviations from trend) when we estimate dynamic parameters, estimate shock processes, calculate business cycle moments, do shock decomposition and perform variance decompositions. There are therefore no data transformations taking place within NEMO and no measurement equations. A future goal is to solve the model around multiple time-varying states, so as to bring the model closer to

[33] NEMO has a separate growth rate for the housing sector.

actual trend developments in the data.

For the demand components (consumption, housing investment, business investment, oil investment, government consumption, imports, traditional exports and oil supply exports) we use the model DORY[34] to filter the series and create the gaps. DORY ensures that the demand component gaps sum to the output gap. Statistical filters (e.g. the Hodrick-Prescott filter) and sector expert judgement are used to estimate the trend for hours worked, house prices, credit variables, the oil price and foreign output. For some series, a three-quarter central moving average procedure is utilised in order to remove noise.

Inflation is detrended by the inflation target of 2.5%.[35] The trend in imported inflation is assumed to be lower than that in overall inflation because of the continuous terms of trade gains from low import price inflation that Norway has enjoyed over the sample period. These gains have been slightly smaller in the latter years and are expected to remain so going forward. An upward trend shift in imported inflation is therefore assumed after 2012.

Due to lower growth rates of trend productivity in recent years, downward shifts in the trend growth rate of real wages were added in 2012 and 2013.[36] The trend shifts in the money market rate are consistent with Norges Bank's published estimates of the neutral interest rate (see Norges Bank's *Monetary Policy Report* (MPR) 3/16, MPR 1/14, MPR 1/12 and MPR 1/10). Norges Bank's estimates are usually expressed as intervals, but NEMO requires point estimates in order to compute the interest rate gap. The point estimate in NEMO has been in the lower end of the estimated interval for the neutral interest rate in recent years.

The neutral foreign money market rate is assumed to be 0.5 percentage point lower than in Norway, reflecting the differences in the inflation target between Norway and our main trading partners in the sample period. The neutral level of market interest rates is calculated based on Norges Bank's internal estimates of various risk premiums.

[34]DORY has been developed by Ørjan Robstad and Kenneth S. Paulsen and will be documented in a forthcoming paper in Norges Bank's Staff Memo series.

[35]The inflation target was reduced in March 2018 to 2%. However, as we calibrate and estimate the model using historical data from 2001 to 2017, the new target is not considered in the detrending exercise.

[36]See the Special Feature on low productivity growth in Norges Bank's *Monetary Policy Report* (MPR) 2/16. All Norges Bank's *Monetary Policy Reports* are available at `http://www.norges-bank.no/en/Published/Publications/Monetary-Policy-Report-with-financial-stability-assessment/`.

E.4 Choice of priors

In total, we estimate 89 parameters, of which 24 are domestic dynamic non-shock-related parameters, 16 are non-shock-related parameters in the foreign block sector, 25 are shock standard errors (of which 5 are in the foreign block), and finally there are 24 shock-persistence parameters. Computations are done using the *RISE* toolbox (see footnote 31). We use two types of priors in estimating the model: system priors and marginal priors.

E.4.1 System priors

The *RISE* toolbox allows for augmenting marginal priors (below) with *system priors*.[37] In contrast to marginal priors that deal with parameters independently, system priors are priors about the model's features and behavior as a system and are modelled with a density function conditional on the model parameters. In theory, the system priors can either substitute or be combined with marginal priors. In our estimation setup, we choose to augment our marginal priors with specific beliefs about the variances of the observed variables. Specifically, we specify our system priors as normal distributions over the variances of the observed variables, $N(\mu, \sigma)$, where we set μ equal to the second-order moment from the data set that is used in the estimation, and a not too restrictive standard deviation (given the magnitude of the variances of the observed variables), σ, equal to 0.01. We did not set prior beliefs about co-variances. The standard deviations of the observables are listed in Table **??** in Section **??**.

E.4.2 Marginal priors

We use a mixed approach in setting the marginal priors. For some parameters, we use the existing literature, empirical analysis and comparable models to find suitable prior values. Additionally, for some parameters, we calibrate the model to match the targeted model moments referred to in the previous section on system priors and set these values as the prior means. Finally, as NEMO is primarily a tool for conducting monetary policy and forecasting, some priors are set based on model users' and sector experts' assessments and judgements of the model's properties, including impulse responses to specific shocks, correlation patterns, and the overall forecasting abilities of the model. This is especially true for the foreign block of the model, where several of the parameters were only weakly identifiable. Table 7 and 8 display the marginal priors.

[37] This is somewhat similar to the framework laid out in Andrle and Benes (2013) and Del Negro and Schorfheide (2008). See the *RISE* website (`https://github.com/jmaih/RISE_toolbox`) for the particular codes.

We choose a beta distribution for the habit persistence parameters with a prior mean of 0.5 and a standard deviation of 0.2. For the habit formation parameter in consumption, we set a tighter prior around 0.8 due to the low consumption volatility observed in the data.

We calibrate the parameters regarding house price expectations and housing investment adjustment costs in order to match the volatilities of housing investment and household credit and to get empirically relevant effects of a monetary policy shock on house prices and housing investment. Similarly, we calibrate the prior mean on investment adjustment costs parameters to match investment volatility. As in Adolfson et al. (2013), we set the prior mean of the curvature parameter in the capital utilisation cost, ϕ_u, to 0.2 to allow for a varying degree of utilisation of the capital stock. Prior means for price and wage adjustment costs are calibrated to be broadly in line with the moments on price and wage inflation rates, but prior standard deviations are set to give room for flexibility in the estimation.

In the banking sector, we estimate the adjustment costs related to changing the deposit, mortgage and corporate lending rates. We calibrate the prior means to match interest pass-through observed in Norwegian data, i.e. close to 1-to-1 for deposit rates and 1-to-0.8 for corporate and household lending rates.

The oil sector in NEMO builds on Bergholt et al. (2019) which forms the basis for our oil-related parameter priors. In particular, we set the prior mean of the rig investment adjustment cost parameter to 6 and the curvature parameter in the rig utilisation cost to 18, both being close to posterior modes in Bergholt et al. (2019). To create sluggishness in the price setting of oil supply goods, we augment the model with adjustment costs. We set high prior means and large standard deviations.

DSGE models tend to be sensitive to external debt-elastic risk premium parameters in the sense that small changes in these parameters can have large effects on the model's behaviour. We estimate ϕ^B based on a tight prior that was set to obtain empirically relevant effects of a shock to real oil prices on the dynamics of the real exchange rate and the Norwegian economy in general. The second risk premium parameter, ϕ^S, was excluded from our estimation due to the low identification strength. We set ϕ^S to 0 to be consistent with the empirically observed response of the real exchange rate to a monetary policy shock.

Shocks There are 26 shocks in NEMO, equal to the number of observable variables. All shocks are assumed to follow first-order autoregressive processes, except for the non-trading-partner output shock which is a pure innovation. Hence, there are 25 persistence parameters.

All shocks are assumed to have an inverse gamma distribution with a standard deviation of 2. Most shocks have a prior mean of 0.01, but some prior means have been somewhat calibrated to better fit some moments. Due to the wide priors on the standard deviations, the shock calibration is expected to have limited impact on the estimation result. The persistence parameters are given a beta distribution with a prior mean of 0.5 and a standard deviation of 0.2.

There is one exception to the above paragraph. The model showed some tendencies in giving the price markup shock "too high" an explanatory power in explaining inflation in the historical shock decomposition. To push the model to use other shocks, we tighten the prior standard deviations of this particular shock and its persistence parameter.

E.5 Posterior results

Table 7 and 8 summarise the estimation results.

The posterior modes show strong habit persistence in consumption (0.94) and housing (0.99), reflecting a large degree of inertia in these variables (although the housing habit parameter is only weakly identifiable). The parameters regarding Rotemberg price adjustment costs have increased compared to the earlier versions of NEMO, indicating a flatter Phillips curve. A relatively flat Phillips curve is also found in the estimation of other DSGE models (see e.g. Adolfson et al. (2013), Dorich et al. (2013) and Rees et al. (2016)).

The posterior modes on the parameters regarding corporate and housing investment adjustment costs move relatively little compared to their prior means in spite of relatively loose prior distributions. This is likely to be a sign of some identification issues (but it may also be due to prior means that correspond well with data and the system priors). In the banking sector, the posterior modes of the interest rate adjustment costs indicate a somewhat lower pass-through of corporate and household interest rates and a higher pass-through for deposit rates, compared to prior means.

Foreign sector parameters move relatively little compared to their prior means. As mentioned above, this is expected as most of these parameters were only weakly identified in the identification analysis and we set quite tight priors.

Most shock persistence parameters came out on the high side. Important exceptions include the price markup shock (for which we set a tight prior) and the wage markup shock, the latter being a sign of wage fluctuations being more transitory than other shocks. Interestingly, similar to the finding in Rees et al. (2016), the foreign inflation shock is much more transitory (0.05) than shocks to foreign output (0.78) and foreign monetary policy (0.32).

We use 30 Markov chains, each of which contains 2.4 million draws generated by the Random Walk Metropolis-Hastings algorithm with an acceptance rate tuned to 0.25. After thinning by a factor of 10 (i.e. keeping every 10th draw), posterior moments were computed from 7.2 million draws, where the first 1.2 million were used as burn-in.[38]

We thin again to keep every remaining 100th draw before calculating the potential scale reduction factor (PSRF) for each parameter as well as the multivariate potential scale reduction factor (MPSRF). The PSRFs for almost all estimated parameters are close to one, implying that convergence is achieved. The MPSRF is close to 1.4.

[38] To cover a large part of the surface of the log-likelihood function and to obtain the needed variation in the posterior draws, we used 900 Markov chains. Each of the 900 chains included 80,000 draws. We then concatenated these different chains to obtain 30 chains with 2.4 million draws each. The resulting posterior densities looked well-behaved.

Table 7: Marginal prior and posterior distributions, dynamic parameters

		Distr.	Prior Mean	Prior S.d.	Posterior Mode	Posterior Mean	Posterior 5%	Posterior 95%
Habit formations								
b^c	Consumption	β	0.8	0.05	0.938	0.945	0.93	0.957
b^h	Housing	β	0.5	0.2	0.987	0.989	0.987	0.99
b^l	Labour	β	0.5	0.2	0.586	0.57	0.535	0.605
b^d	Deposits	β	0.5	0.2	0.481	0.389	0.278	0.49
Adjustment costs etc.								
b^{sa}	House price expect.	β	0.65	0.025	0.639	0.621	0.606	0.635
λ^{sa}	House price expect.	β	0.9	0.05	0.949	0.964	0.95	0.98
ϕ^{PM}	Imports[a]	Γ	9	1	8.301	7.966	7.585	8.334
ϕ^{PM^*}	Exports[a]	Γ	3	1	2.856	2.883	2.693	3.054
ϕ^{PQ}	Domestic goods[a]	Γ	12	1	6.69	6.767	6.7	6.863
ϕ^{W}	Wage inflation[b]	Γ	0.7	0.1	0.667	0.68	0.646	0.713
ϕ_u	Capital util., entrep.	Γ	0.2	0.075	0.219	0.22	0.201	0.24
ϕ_{I1}	Business investment	Γ	10	2	12.543	12.714	11.838	13.57
ϕ_{I2}	Business investment	Γ	170	10	165.662	163.034	158.858	166.972
ϕ_{H1}	Housing investment	Γ	60	5	60.728	61.748	59.614	63.98
ϕ_{H2}	Housing investment	Γ	200	10	199.655	196.241	187.099	205.43
ϕ^{D}	Deposit rate	Γ	0.1	0.05	0.073	0.087	0.076	0.099
ϕ^{e}	Loan rate, entrep.	Γ	15	2	18.501	19.581	18.149	21.096
ϕ^{F}	Loan rate, househ.	Γ	15	2	18.36	18.661	17.828	19.525
ϕ^{RI}	Oil investment	Γ	6	1	8.215	8.149	7.639	8.624
ϕ^{uf}	Oil rigs util.	Γ	18	2	17.795	17.27	16.752	17.71
ϕ^{PR}	Oil supply, dom.[b]	Γ	2	1	1.246	1.182	1.061	1.292
ϕ^{PR^*}	Oil supply, abr.[b]	Γ	2	1	1.723	1.468	0.827	2.167
ϕ^{B}	Risk Prem.	N	0.0015	0.0002	0.00156	0.00159	0.00153	0.00166
Foreign block								
ϕ^{Y*}	Lag, output	N	0.5	0.05	0.615	0.619	0.596	0.643
ψ^{R*}	IS curve	N	1	0.2	0.757	0.724	0.615	0.832
ω^{R*}	Lag, Taylor	β	0.8	0.05	0.841	0.812	0.787	0.835
ω^{P*}	Infl. weight, Taylor	N	1.5	0.1	1.461	1.408	1.366	1.444
ω^{Y*}	Outp. weight, Taylor	N	0.03	0.01	0.04	0.046	0.039	0.054
α^{P*}	Infl. Expectations	N	0.15	0.01	0.15	0.15	0.149	0.15
α^{Y*}	Infl. $\leftarrow$ output	N	0.15	0.05	0.046	0.046	0.039	0.053
ϕ^{P*}	Lag, inflation	N	0.8	0.2	0.886	0.884	0.873	0.894
ϕ^{OP*}	Infl. $\leftarrow$ oil price	N	0.003	0.001	0.001	0	0	0.001
ϕ^{O*}	Output $\leftarrow$ oil price	N	0.005	0.001	0.005	0.005	0.004	0.005
ϕ^{YNTP*}	Output $\leftarrow$ NTP output	N	1	0.2	1.099	1.137	1.04	1.244
λ^{YNTP}	Lag, NTP output	N	0.9	0.2	0.926	0.947	0.914	0.971
ϕ^{ONTP}	NTP output $\leftarrow$ oil price	N	0.002	0.001	0.001	0.002	0.001	0.003
ϕ^{YNTP}	NTP output $\leftarrow$ output	N	0.01	0.002	0.011	0.011	0.011	0.012
β^{O}	Oil price expectations	N	0.2	0.02	0.203	0.202	0.197	0.206
κ^{O}	Oil price demand	N	4	0.1	4.003	3.998	3.983	4.015

Note: After thinning by a factor of 10, posterior moments are computed from 7.2 million draws generated by the Random Walk Metropolis-Hastings algorithm using 30 chains with an acceptance rate tuned to 0.25, where the first 1.2 million are used as burn-in.
[a] Parameter is multiplied by 100 in the model.
[b] Parameter is multiplied by 1000 in the model.

Table 8: Marginal prior and posterior distributions, shock parameters

			Prior		Posterior			
		Distr.	Mean	S.d.	Mode	Mean	5%	95%
Shock persistence								
λ_B	Risk prem.	β	0.5	0.2	0.737	0.732	0.686	0.774
λ_G	Gov. exp.	β	0.5	0.2	0.914	0.948	0.933	0.964
λ_h	Househ. pref.	β	0.5	0.2	0.694	0.658	0.599	0.711
λ_{IH}	Housing investment	β	0.5	0.2	0.861	0.869	0.849	0.888
λ_{IOIL}	Oil investment	β	0.5	0.2	0.834	0.853	0.806	0.894
λ_I	Business investment	β	0.5	0.2	0.646	0.661	0.618	0.703
λ_{z^L}	Productivity (temp.)	β	0.5	0.2	0.804	0.815	0.794	0.835
λ_{MC*}	Marginal costs, abr.	β	0.5	0.2	0.097	0.065	0.034	0.094
λ_ν	Import share	β	0.5	0.2	0.934	0.964	0.949	0.976
$\lambda_{\nu*}$	Export share	β	0.5	0.2	0.924	0.927	0.9	0.953
λ_ϕ	LTV, househ.	β	0.5	0.2	0.783	0.716	0.646	0.776
$\lambda_{\phi^{ent}}$	LTV, entrep.	β	0.5	0.2	0.91	0.884	0.836	0.927
λ_{prem}	Money market risk prem.	β	0.5	0.2	0.817	0.837	0.806	0.868
λ_ψ	Wage markup	β	0.5	0.2	0.28	0.241	0.2	0.279
λ_{θ^e}	Lending rate, entrep.	β	0.5	0.2	0.964	0.966	0.957	0.974
λ_{θ^H}	Price markup	β	0.3	0.02	0.435	0.432	0.428	0.434
$\lambda_{\theta^{IH}}$	Lending rate, househ.	β	0.5	0.2	0.89	0.874	0.848	0.898
λ_u	Consump. pref.	β	0.5	0.2	0.725	0.691	0.641	0.739
λ_{wedge}	Inventories	β	0.5	0.2	0.838	0.868	0.824	0.912
λ_{YO*}	Oil prod., abroad	β	0.5	0.2	0.746	0.741	0.716	0.767
λ_{PO*}	Oil price	β	0.9	0.02	0.874	0.872	0.865	0.879
λ_{R*}	Mon. pol., TP	β	0.5	0.2	0.322	0.342	0.283	0.408
$\lambda_{\theta^{H*}}$	Price markup, TP	β	0.5	0.2	0.052	0.066	0.033	0.104
λ_{U*}	Demand, TP	β	0.5	0.2	0.782	0.816	0.782	0.85
Shock st.dev. (multiplied by 100)								
σ_B	Risk prem.	Γ^{-1}	5	200	0.618	0.633	0.519	0.767
σ_G	Gov. exp.	Γ^{-1}	10	200	0.381	0.401	0.381	0.44
σ_h	Household pref.	Γ^{-1}	1	200	28.677	47.065	36.776	57.85
σ_{IH}	Housing investment	Γ^{-1}	1	200	2.575	2.522	2.356	2.688
σ_{IOIL}	Oil investment	Γ^{-1}	1	200	2.612	2.507	2.021	3.08
σ_I	Business investment	Γ^{-1}	1	200	23.018	24.665	22.951	26.403
σ_{z^L}	Productivity (temp.)	Γ^{-1}	1	200	0.598	0.587	0.545	0.631
σ_{MC*}	Marg. costs, abr.	Γ^{-1}	10	200	34.629	37.145	34.876	39.747
σ_ν	Import share	Γ^{-1}	1	200	0.428	0.485	0.417	0.565
$\sigma_{\nu*}$	Export share	Γ^{-1}	1	200	4.238	4.419	3.825	5.101
$\sigma_{\phi^{ent}}$	LTV, entrep.	Γ^{-1}	1	200	2.59	2.757	2.377	3.203
σ_ϕ	LTV, househ.	Γ^{-1}	1	200	25.423	26.756	23.2	30.894
σ_{prem}	Money market risk prem.	Γ^{-1}	0.05	200	0.037	0.037	0.035	0.038
σ_ψ	Wage markup	Γ^{-1}	200	200	63.31	52.133	46.675	57.846
σ_{θ^e}	Lending rate, entrep.	Γ^{-1}	1	200	84.858	97.346	84.03	112.26
σ_{θ^H}	Price markup	Γ^{-1}	20	0.1	20.145	20.155	20.13	20.183
$\sigma_{\theta^{IH}}$	Lending rate, househ.	Γ^{-1}	1	200	167.942	185.12	174.699	196.939
σ_u	Consump. pref.	Γ^{-1}	1	200	3.021	3.356	2.847	3.91
σ_{wedge}	Inventories	Γ^{-1}	0.1	200	0.184	0.19	0.18	0.201
σ_{YO*}	Oil prod., abroad	Γ^{-1}	6	200	3.409	3.31	3.052	3.546
σ_{PO*}	Oil price	Γ^{-1}	7	200	7.918	8.055	7.864	8.253
σ_{R*}	Mon. pol., TP	Γ^{-1}	0.1	200	0.084	0.086	0.08	0.093
$\sigma_{\theta^{H*}}$	Price markup, TP	Γ^{-1}	1	200	0.833	0.822	0.797	0.844
σ_{U*}	Demand, TP	Γ^{-1}	1	200	1.115	1.104	0.991	1.229
σ_{YNTP}	Global demand	Γ^{-1}	1	200	0.183	0.198	0.17	0.231
Other								
ρ_{ffm}	Oil price ← wage bargaining	N	0.5	0.05	0.527	0.532	0.516	0.55

Note: See notes to Table 7.