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A Model-Based Comparison of Macroprudential Tools *

(A makroprudenciális eszközök modell alapú összehasonlítása)

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Contents

Abstract

We develop a DSGE model to analyze a macroprudential policy framework. We use it to describe the Hungarian economy and the key regulatory constraints implemented there: the loan-to-value and the debt-service-to-income caps imposed on mortgage borrowers and the minimum capital requirement imposed on banks. Our model is novel in the way it treats the borrowing caps as soft constraints, which makes it easy to analyze multiple non-redundant borrowing constraints. We also show an estimation strategy that involves a variation of impulse-response matching and accounts for the lack of historical data concerning the conduct of macroprudential policy, a common problem.

JEL: E37, E44.

Keywords: DSGE, macroprudential, DSTI, LTV, capital requirement, Covid-19.

Összefoglaló

A makroprudenciális szabályozói eszközök hatásvizsgálatához egy DSGE modellt alakítunk ki, amelyben az alábbi alapvető makroprudenciális előírások hatásait vizsgáljuk: a jövedelemarányos törlesztőrészlet mutató (JTM), a hitelfedezeti mutató (HFM), valamint a bankokra kiszabott minimum tőkekövetelmény. Megközelítésünk abból a szempontból egyedi, hogy ezeket az előírásokat laza korlátként kezeli. Ez lehetővé teszi, hogy egyszerre több szabályozás együttes hatását vizsgáljuk a fent említett modellkeretben. Emellett egy becslési módszert is ismertetünk, amely az impluzusválasz-illesztés egy változatán alapul. Ez lehetőséget kínál arra, hogy áthidaljuk a makroprudenciális politikára jellemző, hosszú historikus idősorok hiányából fakadó becslési nehézségeket.

1 Introduction

The Global Financial Crisis of 2007–2009 has been a dramatic event which has an effect on many economies to this day. In terms of the implications for the policy-making, one of the most notable consequences has been the birth of the macroprudential policy framework, a comprehensive approach to regulate the financial system with focus on its stability.

The goal of this paper is to develop (i) a DSGE model that can help compare macroprudential tools and analyze them jointly in a single policy framework and (ii) an estimation strategy that accounts for the lack of historical data concerning the conduct of macroprudential policy. We focus on the Hungarian economy and on the key macroprudential regulatory constraints implemented in Hungary. Namely, we consider the minimum capital requirement imposed on the banks and the loan-to-value (LTV) and debt-service-to-income (DSTI) caps imposed on the mortgage borrowers. We develop a DSGE model with a detailed treatment of the banking sector and macro-financial linkages. The model allows to study the interactions between the macroprudential policies, the credit market, and the rest of the economy. We calibrate the model so that it fits the description of the Hungarian economy between 2014 and 2019. Then, we use a version of impulse-response matching to replicate the impact of the first wave of the Covid-19 Pandemic on the Hungarian economy to say what policies could be justified in those difficult times. To demonstrate the ability of the model to provide policy recommendations, we simulate several hypothetical scenarios, such as changes in regulatory constraints or a deterioration of the housing demand.

For the case of Hungary, we deliver the following findings. First, the impact of the borrowing constraints is limited to the mortgage market; spillovers to the housing market, let alone the rest of the economy, are rather moderate because of the small size of the mortgage market.[1] At the same time, minimum capital requirement has a much broader effect: it affects banks' optimal leverage and therefore both mortgage and corporate lending, whereas the latter has impact on investment and GDP. Second, because we empirically evaluate the key moments of the distributions of borrowers with respect to LTV and DSTI ratios from the credit-registry data and match them in the model, we find that these ratios are different in their efficacy. Compared to the DSTI cap, the LTV constraint is more effective, because it seems to be binding for a greater portion of the borrowers. Finally, we use the data from the first wave of the Covid-19 Pandemic to demonstrate our estimation approach. We conclude that such a dramatic event asks for broad measures, such as raising the minimum capital requirement. Overall, we find that the model produces intuitive results and supports some key macroprudential policies enacted during the Pandemic in Hungary, and we believe it can be applied to other countries and scenarios.

In the existing literature, there are many DSGE models that allow for the analysis of macroprudential policies (e.g., Bianchi and Mendoza, 2018; Lambertini et al., 2013). We follow Benes et al. (2014) and design the banking sector that can expand its balance sheet by issuing loans and creating deposit accounts for the *same* agents, as opposed to banks that would simply channel loanable funds from savers to borrowers, who are separate agents. Such a design is intuitive and easy to communicate to the policy-makers; yet, it is not simply a question of notation, because it is a set-up with profit-seeking banks that actively determine their optimal leverage, which allows for more flexible bank lending and greater effects of financial shocks compared to the model where banks channel the available loanable funds between separate agents (Jakab and Kumhof, 2018).[2] Within the strand of literature that follows Benes et al. (2014), our work is closely related to Clancy, Merola, et al. (2014), Lozej, Rannenberg, et al. (2017), and Lozej et al. (2018). These papers describe DSGE models used to analyze various macroprudential tools, and we rely on them when building such a model that can treat the minimum capital requirement, the LTV cap, and the DSTI cap at the same time.

[1] In fact, the Hungarian ratio of outstanding housing loans to GDP was 7.7 percent at the end of the second quarter of 2020, the lowest in the EU, according to the Housing Market Report published by MNB (the National Bank of Hungary) in November 2020.

[2] When the bank issues a loan, they record it as an asset, while at the same time, they record the same amount as the deposit in the name of the same borrower on the liabilities side. These mechanics may create an impression that banks are unlimited in their capacity to create money. To avoid the misconception, we demonstrate in Section 2 that banks do *not* create money "out of thin air" simply because they can flexibly scale up their balance sheets. There is clearly a limit to their ability to do so: when choosing the optimal leverage, the bank balances between the possibility to profit from the net interest margin on the one side and the risk of default or failure to comply with capital requirements on the other side.

We claim that our model is novel in the way it introduces multiple borrowing constraints. Namely, we design the LTV and DSTI caps as penalties for breaking the limits, which in the end act as soft constraints, so that neither of them is redundant or only occasionally binding. Both constraints matter at all times, and both of them affect the decision of the borrower. There are several examples of general-equilibrium models that contain both LTV and DSTI caps at the same time, and all of them feature the caps as *hard* constraints. Grodecka (2020) introduces both LTV and DSTI caps, which can be binding, potentially at the same time. This is a model with occasionally binding constraints and with four different regimes depending on which of the constraints are binding. As it is the case with such models, both constraints always matter even if they are not binding, because they can potentially become binding in the future. In Greenwald (2018), individual borrowers, depending on their idiosyncratic shocks, may find themselves constrained either by LTV or DSTI cap, whichever is the tightest. Both constraints matter at the same time on the aggregate level, but not for an individual borrower. Compared to the first two mentioned examples, our approach is relatively easy to implement: we can expand the toolkit and introduce more regulatory instruments into the model without much complication. Gelain et al. (2013) and Clancy, Merola, et al. (2014) consider a single hard borrowing constraint that is a linear combination of LTV and DSTI limits. Compared to this set-up, our approach is richer, because it allows our model to consider the fractions of borrowers constrained by LTV and by DSTI caps separately. In fact, our model matches both empirical fractions quite well. In addition, we think that soft constraints are realistic, because in practice, for each individual borrower, there are ways to exceed them, albeit at an additional cost (e.g., through informal arrangements with family members).[3]

A DSGE model is a powerful tool that provides an intuitive interpretation of economic policies and allows to study counterfactual and hypothetical scenarios, but as Benes et al. (2014) point out, using it for the analysis of macroprudential policy is challenging. The typical way to use a DSGE model is to focus on small temporary deviations around the steady state of the economy, most often in a linearized form. This seems like a poor choice when analyzing macroprudential policy, which is often concerned with extreme and highly non-linear deviations from the equilibrium state of the economy, such as potential financial crises. A reduced-form econometric model does not seem to be a better alternative, because the data necessary for its estimation are missing or non-existent for most economies. For example, in case of Hungary, the macroprudential policy framework was introduced in 2014, and most of the implemented caps have not changed since then: it is virtually impossible to estimate their impact outside of a structural model. Therefore, in order to say something about the potential impact of macroprudential policies, we develop a DSGE model and analyze its behavior in various scenarios using a non-linear solution method.

As for our estimation strategy, we rely on the most recent data. It would be extremely difficult to identify the steady state of the Hungarian economy, because available macroeconomic data are short and full of events that could be called structural breaks.[4] We choose to calibrate the steady state of the model so that it corresponds to the recent period of relative tranquility in Hungary between the European Debt Crisis of 2010–2014 and the Covid-19 Pandemic of 2020. We call it ”the reference period” and use 2014q1–2019q4 averages as empirical targets for the calibration. As for the parameters that define the dynamic behavior of the model, we estimate them in such a way that our model can replicate the effect of the first wave of the Covid-19 Pandemic on Hungary's economy, which we have observed in the first two quarters of 2020. To that end, we use a variation of impulse-response matching (Bilbiie et al., 2008; Christiano et al., 2005; Lozej et al., 2018, etc.). Our variation differs from the mentioned examples because we replicate the impact of the Covid-19 Pandemic by means of three simultaneous shocks in the model, which allow us to decompose the effect of the Pandemic according to three key factors: a fall in incomes due to lockdown measures, a fall in export demand, and a deterioration of the housing market. Our estimation strategy puts a lot of emphasis on very few most recent observations: we would like to argue that this approach is justified when the data are lacking and when it is important to provide a policy recommendation concerning the pressing issues, although we do realize that over-identification may be an issue.

The paper proceeds as follows: Section 2 describes the model, Section 3 describes the estimation, Section 4 demonstrates the results, and Section 5 concludes.

[3] We claim that to rely on soft constraints in order to actuate multiple borrowing caps is a novelty. However, on its own, the idea to model individual borrowing limits as soft constraints isn't new, although there are rather few examples (e.g., Alonso, 2018; Achdou et al., 2017; Corugedo, 2002). It is also often the case that, even if the individual borrowers are assumed to face hard constraints in a model, aggregation across agents can result in a soft constraint, or an interest-rate spread on loans that positively depends on aggregate leverage (e.g., Bernanke et al., 1999). Finally, for models of sovereign debt, soft borrowing constraints are a very popular choice (e.g., Schmitt-Grohé and Uribe, 2003).

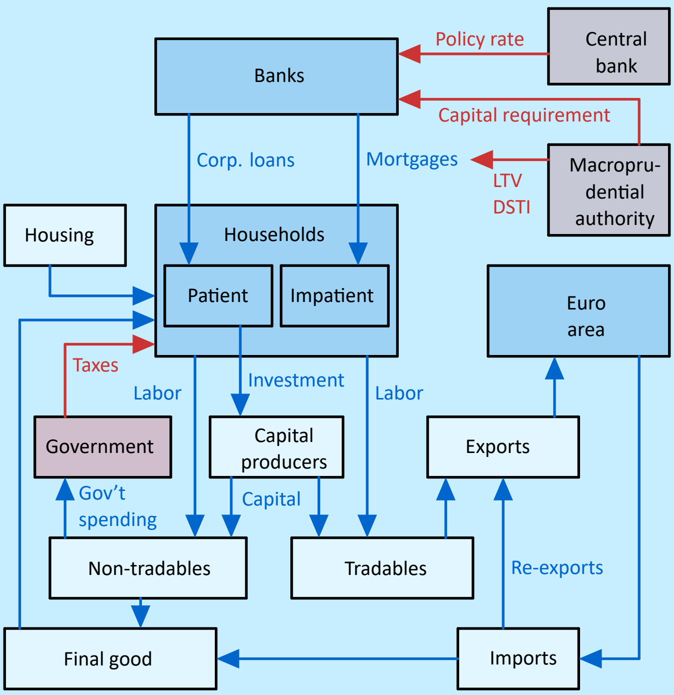
[4] Most available Hungarian macroeconomic data date back to the 1990s and reflect events such as transition towards market-based economy in the 1990s, joining the EU in 2003, the Global Financial Crisis of 2007–2009, and the European Sovereign Debt Crisis of 2010–2014.

2 Model

2.1 GENERAL STRUCTURE

Our model contains a banking sector that collects deposits and issues corporate loans and retail mortgage loans. The banking sector can flexibly expand its balance sheet by issuing loans and creating deposits for the same households, but its scale is limited by credit risk and by macroprudential regulation in form of the minimum capital requirement. There are two types of households: there are Ψ impatient households who borrow mortgages to finance their front-loaded purchases of housing, and there is a unit mass of patient wealthy households who can buy housing stock but who do not borrow mortgages. Both types of households derive utility from deposits (giving rise to the money demand) and therefore hold deposits in the bank. Both types work and earn labor income. However, only patient households own all the firms and earn firm profits. In addition, patient households act as entrepreneurs: they borrow ”corporate” loans to finance purchases of capital and rent capital out to the productive sector. Productive non-tradable sector employs capital and labor to produce output, which is then differentiated by retailers that face nominal rigidities (giving rise to the Phillips curve). The economy is open and small, meaning that there is international trade and capital flows, such that the purchasing power parity and the uncovered interest parity hold. At the same time, the economy does not affect the foreign prices and interest rates. The imported goods are combined either with non-tradable goods for domestic consumption or with tradable inputs for re-export. There is a policy-maker that conducts fiscal policy, monetary policy, and macroprudential policy. The latter is in the form of minimum capital requirement for the banking sector and DSTI and LTV caps for the mortgage market.

Figure 1
An overview of the structure of the model.



In this section, we focus on the key equations that advance the understanding of the model; in Section A of the Appendix, we provide the rest of the equations to complete the description of the model.

2.2 BANKS

There is a unit mass of banks subject to idiosyncratic shocks.[5] Each bank supplies corporate loans L_E to entrepreneurs and mortgage loans $\hat{L}_H$ to impatient households. Note that all the variables specific to impatient households are marked with a hat. The loans are defaultable, and the bank takes entrepreneurs' capital and impatient households' housing stock as collateral. The two types of loans yield aggregate ex-post interest net of costs of default R_E and R_H, respectively. On the liabilities side, the bank has deposits $D + \Psi\hat{D}$ from households, which are promised a pre-determined interest rate R, and equity E_B. The ex-ante balance-sheet identity of the bank in period t is

$$L_{E,t} + \Psi\hat{L}_{H,t} = E_{B,t} + D_t + \Psi\hat{D}_t. \tag{1}$$

The macroprudential authority sets the minimum capital requirement g_t in period t. By the next period, the bank pays a fraction τ_B of assets as a penalty in case it fails to comply, or when its equity *ex post* falls below a regulatory fraction g_t of its assets, so that

$$\left(L_{E,t}R_{E,t} + \Psi\hat{L}_{H,t}R_{H,t}\right)\omega_{B,t+1} - \left(D_t + \Psi\hat{D}_t\right)R_t < g_t\omega_{B,t+1}\left(L_{E,t}R_{E,t} + \Psi\hat{L}_{H,t}R_{H,t}\right).$$

Non-compliance is always a possibility, because each bank's interest income is adjusted by idiosyncratic non-diversifiable bank-specific shock ω_B. We can use the above inequality to define the threshold value for the idiosyncratic shock:

$$\tilde{\omega}_{B,t} = \frac{(D_{t-1} + \Psi\hat{D}_{t-1})R_{t-1}}{(1-g_{t-1})(L_{E,t-1}R_{E,t-1} + \Psi\hat{L}_{H,t-1}R_{H,t-1})}. \tag{2}$$

If a particular bank's idiosyncratic shock falls below the threshold $\tilde{\omega}_{B,t}$, they have to pay the penalty. To facilitate aggregation, we assume that after the idiosyncratic shocks are realized and the penalties are paid, the individual payoffs of the banks are pooled so that all the banks remain equivalent *ex ante* in every period t. Let us assume a log-normal distribution for $\omega_{B,t}$: $\ln\omega_{B,t} \sim \mathcal{N}(-\sigma_B^2/2, \sigma_B^2)$, so that $\mathbf{E}[\omega_{B,t}] = 1$. Then, we can define variable $z_{B,t}$:

$$z_{B,t} = \frac{\ln\tilde{\omega}_{B,t}}{\sigma_B} + \frac{\sigma_B}{2}. \tag{3}$$

This allows us to use the c.d.f. of the standard normal distribution $\Phi(\cdot)$ to define the bank's objective function. Every period t, conditional on equity E_{t-1} carried over from the previous period, the bank chooses optimal amounts of loans, deposits, and equity to maximize the net expected payoff:

$$\max_{\{E_t, L_{E,t}, \hat{L}_{H,t}, D_t, \hat{D}_t\}} \mathbf{E}_t\left\{\beta\frac{\Lambda_{t+1}}{\Lambda_t}\left[R_{E,t}L_{E,t} + R_{H,t}\Psi\hat{L}_{H,t} - R_t(D_t + \Psi\hat{D}_t) - \tau_B\Phi(z_{B,t+1})(L_{E,t} + \Psi\hat{L}_{H,t})\right]\right\} - E_{B,t} - \frac{\xi_B}{2}\Omega_{B,t}^2E_{B,t}. \tag{4}$$

The bank has to invest equity $E_{B,t}$ in period t in exchange for a payoff in period $t+1$, which is the net interest margin minus the expected penalty for failure to comply with the minimum-capital requirement. The stochastic discount factor $\beta\Lambda_{t+1}/\Lambda_t$ multiplies the expected payoff because the bank belongs to the patient households. The term $\Omega_{B,t}$ reflects the fact that it is costly for the bank to adjust its equity:

$$\Omega_{B,t} = \ln\left(\frac{E_{B,t}}{E_{B,t-1}R_{B,t}(1-\delta_B)}\right), \tag{5}$$

where R_B is the banking sector's pooled ex-post return on equity:

$$E_{B,t-1}R_{B,t} = R_{E,t-1}L_{E,t-1} + R_{H,t-1}\Psi\hat{L}_{H,t-1} - R_{t-1}\left(D_{t-1} + \Psi\hat{D}_{t-1}\right) - \tau_B\Phi(z_{B,t})\left(L_{E,t-1} + \Psi\hat{L}_{H,t-1}\right). \tag{6}$$

In other words, if the bank did not actively manage the equity, the equity would equal the retained profit $E_{B,t-1}R_{B,t}(1-\delta_B)$, whereas a fraction δ_B of net income would be paid out as dividend. As the banks choose the optimal equity size, the corresponding first-order condition takes the cost of equity adjustment into account:

$$\beta\mathbf{E}_t\left\{\frac{\Lambda_{t+1}}{\Lambda_t}R_{B,t+1}\right\} = 1 + \xi_B\Omega_{B,t} + \frac{\xi_B}{2}\Omega_{B,t}^2. \tag{7}$$

It is often assumed in the literature that the bank equity is fixed, which is a limiting case in our specification when the equity adjustment cost parameter ξ_B is infinite. Such a case would imply that the bank's net return on equity is always paid out as

[5] Wherever it is present in the model, we model the idiosyncratic risk in the same manner as the entrepreneurial risk in Bernanke et al. (1999). To be precise, we should denote variables pertaining to each individual bank with an index $i \in [0,1]$, but we omit the index for brevity: in the end, the analysis boils down to equations describing the aggregate banking sector.

dividends. More generally, we allow the banks to change the equity over time, although we don't fully exploit this flexibility, since we assume high adjustment costs in order to reflect the fact that banks find it hard to adjust equity in the short run. We discuss this issue further when we assess the impact of macroprudential policies in Section 4.1.

Given equity $E_{B,t}$ and taking interest rates as exogenous, the bank chooses its loan portfolio (and the corresponding amount of deposits) to maximize the expected payoff (4) subject to constraints (1) and (2). For clarity, let us use the balance-sheet identity (1) to substitute the deposits out of the bank's objective function (4) and re-write it as follows:

$$\mathbf{E}_t\left\{\beta\frac{\Lambda_{t+1}}{\Lambda_t}\Big[(R_{E,t}-R_t)L_{E,t}+(R_{H,t}-R_t)\Psi\hat{L}_{H,t}-\tau_B\Phi(z_{B,t+1})(L_{E,t}+\Psi\hat{L}_{H,t})-E_{B,t}R_t\Big]\right\}-E_{B,t}-\frac{\xi_B}{2}\Omega_{B,t}^2E_{B,t}. \tag{8}$$

In this form, it is clear that the bank, when deciding upon the scope of lending, balances the interest spread on the one hand and the risk of failure to comply with the minimum capital requirement on the other. In addition to the higher expected cost of non-compliance, as it becomes clear in the section about the loan market below, more lending is associated with higher risk of borrower default, which lowers the interest spread. These two considerations clearly tell that, despite the banks being able to issue loans and deposits to the same clients, they cannot do so indefinitely, and therefore they do not create money ”out of thin air”. The first-order conditions with respect to $L_{E,t}$ and $L_{H,t}$ define the optimal interest rates on loans and further illustrate the bank's trade-off:

$$R_{E,t}-R_t=\mathbf{E}_t\left\{\tau_B\Phi(z_{B,t+1})+\frac{\tau_B}{\sigma_B}\phi(z_{B,t+1})\left(L_{E,t}+\Psi\hat{L}_{H,t}\right)\left(\frac{1}{L_{E,t}+\Psi\hat{L}_{H,t}-E_{B,t}}-\frac{R_{E,t}}{L_{E,t}R_{E,t}+\Psi\hat{L}_{H,t}R_{H,t}}\right)\right\}; \tag{9}$$

$$R_{H,t}-R_t=\mathbf{E}_t\left\{\tau_B\Phi(z_{B,t+1})+\frac{\tau_B}{\sigma_B}\phi(z_{B,t+1})\left(L_{E,t}+\Psi\hat{L}_{H,t}\right)\left(\frac{1}{L_{E,t}+\Psi\hat{L}_{H,t}-E_{B,t}}-\frac{R_{H,t}}{L_{E,t}R_{E,t}+\Psi\hat{L}_{H,t}R_{H,t}}\right)\right\}. \tag{10}$$

Section B of the Appendix contains a detailed derivation of the bank's optimality conditions.

2.3 LOAN MARKET

Like in the case of banks, in order to introduce the risks associated with loans and yet keep the model tractable, we model each household as a unit mass of agents that are identical *ex ante* and who follow the household's optimal policy and borrow identical loans. *Ex post*, some agents will default or find themselves unable to meet macroprudential constraints due to idiosyncratic risk. Yet, all the agents' payoffs are going to be pooled across the household, so that by the next period, all agents become identical again.

2.3.1 MORTGAGES

In period $t-1$, an impatient household agent takes a mortgage loan $\hat{L}_{H,t-1}$ from the bank at the interest rate $\tilde{R}_{H,t}$ assigned to it. The interest rate is adjustable: the bank will set it optimally in period t, depending on the state of the economy. The mortgage loan obtained in period $t-1$ is used to buy housing stock $\hat{H}_{t-1}$ at price $Q_{H,t-1}$. Next period, the value of the outstanding debt will be $\hat{L}_{H,t-1}\tilde{R}_{H,t}$, and the value of the housing stock is going to be $\hat{H}_{t-1}Q_{H,t}(1-\delta_H)\omega_{H,t}$, where δ_H is the rate of housing-stock depreciation and ω_H is a log-normally distributed idiosyncratic shock, such that $\ln\omega_H\sim\mathcal{N}(-\sigma_H^2/2,\sigma_H^2)$. This shock reflects the fact that the housing market is extremely fragmented, with each house having unique combination of characteristics and subject to fluctuations in value due to local neighborhood effects.

The macroprudential authority imposes borrowing caps, which we model as distortionary taxes that discourage the household from exceeding the caps. The impatient household expects to pay macroprudential taxes in case its agents fail to comply with the regulatory caps on the size of the mortgage debt.

The first macroprudential limit g_{LTV} is imposed on the loan-to-value ratio, such that the household agent pays a penalty in case the LTV exceeds the limit:

$$\frac{\hat{L}_{H,t-1}\tilde{R}_{H,t}}{\hat{H}_{t-1}Q_{H,t}(1-\delta_H)\omega_{H,t}}>g_{LTV,t-1}.$$

We can use this inequality to define the threshold $\tilde{\omega}_{LTV,t}$:

$$\tilde{\omega}_{LTV,t}=\frac{\hat{L}_{H,t-1}\tilde{R}_{H,t}}{\hat{H}_{t-1}Q_{H,t}(1-\delta_H)g_{LTV,t-1}}, \tag{11}$$

and the corresponding threshold $z_{LTV,t}$ defined for the standard normal distribution:

$$z_{LTV,t} = \frac{\ln \tilde{\omega}_{LTV,t}}{\sigma_H} + \frac{\sigma_H}{2}. \tag{12}$$

An agent who does not comply with the imposed cap due to a bad realization of the idiosyncratic housing-stock shock pays a penalty proportionate to the size of the mortgage loan $\tau_{LTV}\hat{L}_{H,t-1}$. Therefore, the household as a whole expects to pay $\tau_{LTV}\hat{L}_{H,t-1}\Phi(z_{LTV,t})$.

The second limit is the DSTI cap, or the limit imposed on the debt service to income. In practice, this cap constrains borrower's loan payments relative to income. There are two complications related to the inclusion of this instrument into the model. The first is that so far, the only source of idiosyncrasy among the agents, the shock to the housing stock, does not allow to create any heterogeneity among household agents in terms of their ability to comply with the DSTI cap: the payable amount is the same for every agent, and so is the wage income. The evidence suggests, however, that a fraction of households is constrained by the DSTI cap. To reflect this fact, we introduce an idiosyncratic shock to labor productivity $\omega_{W,t} \sim \mathcal{N}(-\sigma_W^2/2, \sigma_W^2)$, such that a household agent earns $\hat{W}_t\omega_{W,t}$, whereas the borrowing household as a whole earns $\hat{W}_t$. The second complication is that the loans in the model are extended for one quarter, whereas mortgage loans have long terms in reality. In order for the DSTI cap $g_{DSTI,t}$ to be closely related to the real-world policy, let us use the annuity formula and compute the quarterly fixed payment F_t that would pay down a mortgage loan extended for n quarters, which represents the average term of the mortgage loan, given the size of the loan $\hat{L}_{H,t-1}$ and the interest rate $\tilde{R}_{H,t}$:

$$F_t = \hat{L}_{H,t-1}\frac{\tilde{R}_{H,t} - 1}{1 - \tilde{R}_{H,t}^{-n}} \tag{13}$$

Therefore, when the macroprudential authority imposes a DSTI cap g_{DSTI}, a fraction of household agents will fail to comply with the regulation due to bad realizations of idiosyncratic income shock, and thus pay the penalty $\tau_{DSTI}\hat{L}_{H,t-1}$: $F_t > \hat{W}_t\omega_{W,t}g_{DSTI,t-1}$. Similarly with the case of LTV caps, we define the threshold for the idiosyncratic income shock and the corresponding value for the standard normal distribution:

$$\tilde{\omega}_{DSTI,t} = \frac{F_t}{\hat{W}_t g_{DSTI,t-1}}; \tag{14}$$

$$z_{DSTI,t} = \frac{\ln \tilde{\omega}_{DSTI,t}}{\sigma_W} + \frac{\sigma_W}{2}. \tag{15}$$

The household as a whole expects to pay $\tau_{DSTI}\hat{L}_{H,t-1}\Phi(z_{DSTI,t})$ in penalties.

In addition to the failure to comply with macroprudential limits, a particularly unlucky household agent may find it necessary to default on the mortgage. An important question is whether the household defaults when the mortgage goes underwater (i.e. when the value of the house is less than the outstanding debt) or when the household is so liquidity-constrained that it cannot make the currently outstanding mortgage payments. We have attempted both types of default decisions in our model, with similar results. The decision can also depend on a combination of the two factors, as in Clancy, Merola, et al. (2014), for example. In the end, we assume that equity considerations are the main factor behind the decision to default, even when there can be additional sanctions imposed on the borrower on top of the seizure of the collateral. A liquidity-constrained household could refinance the mortgage or make some other arrangements to cover the shortage in order to make the payment, provided that the shortage is temporary. Therefore, we follow the popular approach (e.g., Forlati and Lambertini, 2011) and assume that the household will default if the value of the collateral falls below the value of the outstanding debt:

$$\hat{H}_{t-1}Q_{H,t}(1 - \delta_H)\omega_{H,t} < \hat{L}_{H,t-1}\tilde{R}_{H,t}.$$

Let us define the threshold value of the idiosyncratic shock for the decision to default:

$$\tilde{\omega}_{H,t} = \frac{\hat{L}_{H,t-1}\tilde{R}_{H,t}}{\hat{H}_{t-1}Q_{H,t}(1 - \delta_H)}. \tag{16}$$

Whenever the idiosyncratic housing-stock shock falls below the threshold, the household will default on the mortgage. In this case, the household loses the house, the bank collects a fraction $1 - \mu_H$ of the value of the house, and a small fraction μ_H is wasted due to costs associated with the mortgage foreclosure. Following Bernanke et al. (1999), for a log-normally distributed variable $\ln \omega_H$, let us make the following definitions:

$$
\begin{aligned}
z_{H,t} &= (\ln \tilde{\omega}_{H,t})/\sigma_H + \sigma_H/2;\\
G_{H,t} &= \Phi(z_{H,t} - \sigma_H);\\
\Gamma_{H,t} &= \Phi(z_{H,t} - \sigma_H) + \tilde{\omega}_{H,t}\big(1 - \Phi(z_{H,t})\big),
\end{aligned}
$$

where Φ is the c.d.f. of the standard normal distribution. A mortgage contract is such that the household agent and the bank *ex ante* co-pay for the purchase of the house, while *ex post* the household agent expects to collect the share $1 - \Gamma_{H,t}$ of the house's expected value $\hat{H}_{t-1}Q_{H,t}(1 - \delta_H)$, the bank expects to collect $\Gamma_{H,t} - \mu_H G_{H,t}$, and $\mu_H G_{H,t}$ is expected to be wasted as a cost of default. Effectively, the impatient household (and each of its agents) optimally chooses the combination of the loan principal and the housing stock $\{\hat{L}_{H,t-1}, \hat{H}_{t-1}\}$ in period $t-1$, and the bank sets the mortgage rate $\tilde{R}_{H,t}$ and the corresponding default threshold $\tilde{\omega}_{H,t}$ in period t, such that the bank's participation constraint is satisfied:

$$
R_{H,t-1}\hat{L}_{H,t-1} = \hat{H}_{t-1}Q_{H,t}(1 - \delta_H)\big(\Gamma_{H,t} - \mu_H G_{H,t}\big). \tag{17}
$$

That is, the bank adjusts the mortgage rate $\tilde{R}_{H,t}$ so that it earns the same pre-determined interest net of the default cost $R_{H,t-1}$ in every state of the economy. The risk of default is borne by the household.

2.3.2 CORPORATE LOANS

Every agent of the patient household is an entrepreneur that chooses the amount of capital purchases that maximize the return on their entrepreneurial activities. The entrepreneur spends $Q_{K,t-1}K_{t-1}$ on capital in period $t-1$ and earns $Q_{K,t-1}K_{t-1}R_{K,t}\omega_{K,t}$ in the next period, where $R_{K,t}$ is aggregate capital return and $\omega_{K,t}$ is idiosyncratic shock to the entrepreneur's return, such that $\ln \omega_K \sim \mathcal{N}(-\sigma_K^2/2, \sigma_K^2)$. Using capital as collateral, the entrepreneur can borrow $L_{E,t-1}$ at an adjustable rate $\tilde{R}_{E,t}$ determined by the bank in period t. The entrepreneur may choose to default and lose earnings $Q_{K,t-1}K_{t-1}R_{K,t}\omega_{K,t}$ if the outstanding debt exceeds the earnings. We can therefore define the default threshold:

$$
\tilde{\omega}_{K,t} = \frac{L_{E,t-1}\tilde{R}_{E,t}}{Q_{K,t-1}K_{t-1}R_{K,t}}. \tag{18}
$$

If we define $\Gamma_{K,t}$ and $G_{K,t}$ in the same way as in the case of mortgages, we can show that the entrepreneur expects to retain a fraction $1 - \Gamma_{K,t}$ of earnings from capital after paying the costs of corporate loan, and the bank expects a fraction $\Gamma_{K,t} - \mu_K G_{K,t}$, whereas $\mu_K G_{K,t}$ is expected to be wasted due to default. The patient household is therefore subject to the bank participation constraint specific to the corporate loan:

$$
R_{E,t-1}L_{E,t-1} = K_{t-1}Q_{K,t-1}R_{K,t}(\Gamma_{K,t} - \mu_K G_{K,t}). \tag{19}
$$

2.4 HOUSEHOLDS

2.4.1 IMPATIENT HOUSEHOLDS

We mark all the variables specific to impatient households with hats. Impatient households maximize their lifetime utility with respect to housing, consumption, and deposit holdings:

$$
\sum_{t=0}^{\infty} \hat{\beta}^t \mathbf{E}_t \left\{ (1-\chi)\ln(\hat{C}_t - \chi\hat{C}_{t-1}) + \psi_t \ln \hat{H}_t + \zeta \frac{1}{1-\iota}\left(\frac{\hat{D}_t}{P_t}\right)^{1-\iota} \right\}.
$$

Parameter $0 < \hat{\beta} < 1$ is the discount factor; χ represents consumption habits; exogenous variable ψ_t stands for housing preferences, and changes in this variable can be interpreted as housing-demand shocks. Deposits in the utility give rise to the demand for money, and ι is the demand elasticity. The budget constraint is the following:

$$
\begin{aligned}
P_t\hat{C}_t + \hat{D}_t + Q_{H,t}\hat{H}_t - \hat{L}_{H,t} = R_{t-1}\hat{D}_{t-1} + Q_{H,t}\hat{H}_{t-1}(1 - \delta_H)(1 - \Gamma_{H,t}) - \\
- \hat{L}_{H,t-1}\big(\tau_{LTV}\Phi(z_{LTV,t}) + \tau_{DSTI}\Phi(z_{DSTI,t})\big) + \hat{V}_t - \hat{T}_t + \hat{W}_t.
\end{aligned} \tag{20}
$$

The household earns wage income $\hat{W}_t$ and purchases consumption good $\hat{C}_t$ at a price P_t and housing stock $\hat{H}_t$ at a price $Q_{H,t}$. It places a deposit $\hat{D}_t$ at a pre-determined interest R_t. Using housing as collateral, the household can borrow a mortgage loan $\hat{L}_{H,t}$. The retained housing net of housing depreciation and mortgage payments, when pooled across all household agents, is $\hat{H}_{t-1}(1-\delta_H)(1-\Gamma_{H,t})$. In addition, for agents that violate the LTV or DSTI caps, the household pays a penalty τ_{LTV} or τ_{DSTI} to the macroprudential authority, which in turn transfers the collected penalties back in form of a lump-sum transfer $\hat{V}_t$. The household also pays a lump-sum tax $\hat{T}_t$ to the government.

The household optimally chooses $\{\hat{C}_t, \hat{D}_t, \hat{H}_t, \tilde{R}_{H,t+1}, \hat{L}_{H,t}\}$ subject to constraints (11)–(17) and (20). The first-order conditions are standard-looking; they are provided in the Appendix. Note, however, that all the expressions that involve *pooled* idiosyncratic payoffs of the household from its agents are equivalent to each household agent's *expected* payoff when they formulate the optimal policy. This is the strength of the chosen approach to pool all the payoffs across household agents (and banks, for that matter): we work with one or two representative agents and therefore keep the model highly tractable, yet the agents' decisions still account for idiosyncratic risk associated with loans. We can still talk about the share of borrowers who default on their loans or find themselves constrained by the macroprudential caps, which helps us estimate the model.

2.4.2 PATIENT HOUSEHOLDS

Patient households have a higher value of the discount factor $\hat{\beta} < \beta < 1$, but otherwise their utility function is the same:

$$\sum_{t=0}^{\infty} \beta^t \mathbf{E}_t \left\{ (1-\chi)\ln(C_t - \chi C_{t-1}) + \psi_t \ln H_t + \zeta \frac{1}{1-\iota}\left(\frac{D_t}{P_t}\right)^{1-\iota} \right\}.$$

Their budget constraint is also similar:

$$P_t C_t + D_t + Q_{H,t}H_t + Q_{K,t}K_t - L_{E,t} = W_t + R_{t-1}D_{t-1} + R_{K,t}Q_{K,t-1}K_{t-1}(1-\Gamma_{K,t}) + Q_{H,t}H_{t-1}(1-\delta_H) - T_t + \Pi_t. \quad (21)$$

What distinguishes a patient household is that, first, it does not use mortgage financing to pay for housing by assumption; only impatient households get mortgages. Second, a patient household acts as an entrepreneur that buys capital stock K_t at price $Q_{K,t}$. Using capital stock as collateral, it can take out a corporate loan $L_{E,t}$. The return on capital net of costs of corporate loan such as interest and losses associated with default is $R_{K,t}(1-\Gamma_{K,t})$, where $R_{K,t}$ is the aggregate return on capital. And third, a patient household earns profit Π_t from all the banks and firms that it owns.

The household optimally chooses $\{C_t, D_t, H_t, K_t, \tilde{R}_{E,t+1}, L_{E,t}\}$ subject to the constraints (18), (19), and (21). We provide the first-order conditions in the Appendix.

2.5 PRODUCTION

2.5.1 CAPITAL PRODUCERS

Capital producers can combine capital retained from the previous period with investment I_t to produce new capital stock:

$$K_t = K_{t-1}(1-\delta_K) + I_t, \quad (22)$$

where δ_K is the rate of capital depreciation. Each period, they purchase retained capital from entrepreneurs at price $Q_{K,t}$, pay the costs of investment, and sell the new capital stock at the same price $Q_{K,t}$ back to the entrepreneurs. Correspondingly, capital producers maximize the following profit:

$$\Pi_{K,t} = Q_{K,t}K_t - Q_{K,t}K_{t-1}(1-\delta_K) - I_t P_t - \frac{\varphi}{2}\left(\frac{I_t}{K_{t-1}} - \delta_K\right)^2 K_{t-1}P_t, \quad (23)$$

where the last term represents capital-adjustment costs, which are non-zero if $K_t \neq K_{t-1}$. The profit $\Pi_{K,t}$ is then paid to the patient households. Given that the retained capital stock is pre-determined, the capital producers choose the level of investment to maximize the profit subject to the capital-accumulation constraint (22), which yields the equation for capital supply:

$$Q_{K,t} = P_t\left(1 + \varphi\left(\frac{I_t}{K_{t-1}} - \delta_K\right)\right). \quad (24)$$

2.5.2 NON-TRADABLE SECTOR

Firms in the non-tradable sector combine effective labor $A_{Y,t}N_{Y,t}$ and capital $K_{Y,t-1}$ to produce output Y_t:

$$Y_t = (A_{Y,t}N_{Y,t})^{1-\alpha}K_{Y,t-1}^{\alpha}. \tag{25}$$

$A_{Y,t}$ is the exogenous labor-augmenting technology process. It is convenient to think of a production department where each firm produces output and sells it to the distribution department at marginal cost $U_{Y,t}$ while making zero profit:

$$U_{Y,t}Y_t - W_tN_{Y,t} - W_{K,t}K_{Y,t-1} = 0,$$

so that the optimal input combination is determined by the following conditions:

$$\alpha U_{Y,t}Y_t = K_{Y,t-1}W_{K,t}; \tag{26}$$

$$(1-\alpha)U_{Y,t}Y_t = N_{Y,t}W_t. \tag{27}$$

We can use the capital rent W_K defined by equation (26) to express the return on capital. To that end, we can think of an entrepreneur that buys capital, rents it out to the firms in the non-tradable sector, and then sells what is left after depreciation:

$$R_{K,t} = \frac{W_{K,t} + Q_{K,t}(1-\delta_K)}{Q_{K,t-1}}. \tag{28}$$

In the distribution department, each firm pays $U_{Y,t}Y_t$ for output Y_t and then distributes it at price $P_{Y,t}$, while exerting some monopoly power due to cost-free product differentiation. The monopoly power manifests itself as the following downward-sloping firm-specific demand curve:

$$Y_t = \left(\frac{P_{Y,t}}{\bar{P}_{Y,t}}\right)^{-\nu}\bar{Y}_t. \tag{29}$$

Notice that we indicate the variables out of an individual firm's control with bars. The distributor expects the following discounted profit:

$$\sum_{t=0}^{\infty}\beta^t\mathbf{E}_t\left\{\Lambda_t\left(P_{Y,t}Y_t - U_{Y,t}Y_t - \frac{\xi_Y}{2}\left(\frac{P_{Y,t}}{P_{Y,t-1}} - \frac{\bar{P}_{Y,t-1}}{\bar{P}_{Y,t-2}}\right)^2\bar{P}_{Y,t}\bar{Y}_t\right)\right\},$$

where the last term in the brackets represents the price-adjustment cost of the Rotemberg variety. The distributor chooses $P_{Y,t}$ to maximize the expected profit subject to equation (29), and the optimal behavior balances changes in prices and in output:

$$\nu - 1 = \nu\frac{U_{Y,t}}{P_{Y,t}} - \xi_Y\left(\frac{P_{Y,t}}{P_{Y,t-1}} - \frac{P_{Y,t-1}}{P_{Y,t-2}}\right)\frac{P_{Y,t}}{P_{Y,t-1}} + \beta\mathbf{E}_t\left\{\frac{\Lambda_{t+1}}{\Lambda_t}\frac{Y_{t+1}}{Y_t}\xi_Y\left(\frac{P_{Y,t+1}}{P_{Y,t}} - \frac{P_{Y,t}}{P_{Y,t-1}}\right)\left(\frac{P_{Y,t+1}}{P_{Y,t}}\right)^2\right\}. \tag{30}$$

2.5.3 IMPORTS AND EXPORTS

Let $P^*_{M,t}$ be the exogenous price of imported good in foreign currency and S_t be the exchange rate. The price of goods imported from abroad is defined by the purchasing power parity:

$$P_{M,t} = P^*_{M,t}S_t, \tag{31}$$

where $P_{M,t}$ is the price of imports in local currency units and S_t is the exchange rate. The export price is related to the import price through the effective terms of trade Θ_t, which are a stochastic exogenous process:

$$P_{X,t} = \Theta_tP_{M,t} \tag{32}$$

Exporters combine locally produced goods Z_t with imported goods $M_{X,t}$ in order to produce exports. For this combination, we assume Leontieff production function:

$$X_t = \min\left\{\frac{Z_t}{1-\alpha_X}, \frac{M_{X,t}}{\alpha_X}\right\},$$

which implies that the optimal policy for exporters is to employ the two inputs in fixed proportions:

$$Z_t = (1-\alpha_X)X_t, \tag{33}$$

$$M_{X,t} = \alpha_XX_t. \tag{34}$$

It also implies that the marginal cost of the export good combines the import price and the marginal cost of the domestically produced component in fixed proportions as well:

$$U_{X,t} = \alpha_X P_{M,t} + (1-\alpha_X) U_{Z,t}. \quad (35)$$

The domestic component of exports Z_t is produced using labor $N_{Z,t}$ and capital stock K_Z:

$$Z_t = K_Z^{\alpha_Z} N_{Z,t}^{1-\alpha_Z}. \quad (36)$$

We treat the capital in export sector as fixed, in order to reflect the fact that there is a large presence of foreign capital in Hungary (e.g. in automotive sector). Consequently, the firms producing the domestic component of exports only choose the optimal amount of labor:

$$(1-\alpha_Z) U_{Z,t} Z_t = W_t N_{Z,t}. \quad (37)$$

In order to determine the price of exports $P_{X,t}$, the exporting firms maximize the following lifetime profits:

$$\sum_{t=0}^{\infty} \beta^t \mathbf{E}_t \left\{ \Lambda_t \left[P_{X,t} X_t \left(1 - \frac{\xi_X}{2} \left(\ln \frac{X_t}{X_{t-1}} \right)^2 \right) - U_{X,t} X_t \right] \right\},$$

where ξ_X reflects the costs of adjusting the exports. The optimal pricing behavior of the sector takes these costs into account:

$$\beta \mathbf{E}_t \left\{ \frac{\Lambda_{t+1}}{\Lambda_t} \frac{P_{X,t+1}}{P_{X,t}} \frac{X_{t+1}}{X_t} \xi_X \ln \frac{X_{t+1}}{X_t} \right\} = \frac{U_{Z,t}}{P_{X,t}} (1-\alpha_X) + \xi_X \ln \frac{X_t}{X_{t-1}} - \left(1 - \frac{\xi_X}{2} \left(\ln \frac{X_t}{X_{t-1}} \right)^2 \right). \quad (38)$$

2.5.4 FINAL GOODS

Final goods are produced as a CES composite of domestically produced non-tradables (net of government purchases) and imported goods, and are used for domestic consumption and investment:

$$C_t + I_t = \left[(1-\alpha_F)^{\frac{1}{\nu_F}} (Y_t - G_t)^{\frac{\nu_F - 1}{\nu_F}} + \alpha_F^{\frac{1}{\nu_F}} M_{Y,t}^{\frac{\nu_F - 1}{\nu_F}} \right]^{\frac{\nu_F}{1-\nu_F}},$$

where α_F is the share of imported goods and ν_F is the elasticity of substitution between the two types of goods. Firms producing the final goods maximize the following profit:

$$P_t (C_t + I_t) - P_{Y,t} (Y_t - G_t) - P_{M,t} M_{Y,t},$$

which results in the following optimality conditions:

$$Y_t - G_t = (1-\alpha_F) \left(\frac{P_{Y,t}}{P_t} \right)^{-\nu_F} (C_t + I_t); \quad (39)$$

$$M_{Y,t} = \alpha_F \left(\frac{P_{M,t}}{P_t} \right)^{-\nu_F} (C_t + I_t). \quad (40)$$

2.5.5 HOUSING CONSTRUCTION

We introduce a rigid housing sector, in which the total housing supply remains fixed:

$$H_t + \Psi \hat{H}_t = \bar{H}. \quad (41)$$

That is, every period, the amount of newly produced housing is just enough to replace depreciation $\delta_H \bar{H}$. This amount is constructed free of charge, and the profits from selling this additional housing stock equal to $\delta_H \bar{H} Q_{H,t}$ are given to the patient households.

2.5.6 LABOR SUPPLY

Note that the labor supply is fixed. Each household supplies one unit of labor, the unit mass of patient households have labor productivity equal to one, and Ψ impatient households have a higher productivity $\kappa > 1$:

$$N_{Y,t} + N_{Z,t} = 1 + \Psi\kappa. \quad (42)$$

We assume that households with mortgages have higher productivity in order to match the data on total stock of mortgages and average DSTI at the same time. It is also intuitive: a typical life-cycle income profile of a household suggests that people tend to pay down mortgages during the period of life when they are the most productive. We can therefore relate the wage rates of the two households as follows:

$$\hat{W}_t = \kappa W_t. \quad (43)$$

2.6 MONETARY AND FISCAL POLICY

We do not assume any knowledge about the reaction function of the monetary authority. We prefer to treat the interest rate R_t set by the authority as given. Fiscal authority executes government purchases, which are assumed to be a constant fraction γ of the non-tradable output. These purchases are financed by lump-sum tax imposed on every household and by the government debt B_t:

$$T_t + \Psi\hat{T}_t + B_t - B_{t-1}R_{t-1} = \gamma Y_t P_{Y,t}. \quad (44)$$

2.7 OPEN-ECONOMY CONSIDERATIONS

Uncovered interest parity (UIP) relates the domestic interest rate to the foreign interest rate R^*, which we interpret as the one prevailing in the Eurozone:

$$R_t = R_t^* \frac{\mathbf{E}_t\{S_{t+1}\}}{S_t} + \eta \left(e^{\frac{B_t}{GDP_t} - \frac{B}{GDP}} - 1 \right), \quad (45)$$

where B/GDP is the steady-state debt-to-GDP ratio.[6] The balance of payments equation is also standard:

$$P_{X,t}X_t - P_{M,t}M_t = R_{t-1}B_{t-1} - B_t. \quad (46)$$

2.8 EXOGENOUS SHOCK PROCESSES

We have introduced three types of exogenous shock processes, which are labor-augmenting technology in the non-tradable sector (domestic productivity), weight of housing in the utility (housing demand), and terms of trade:

$$\ln A_{Y,t} = \rho_Y \ln A_{Y,t-1} + \sigma_Y \varepsilon_{Y,t}, \quad \varepsilon_{Y,t} \sim \mathcal{N}(0,1); \quad (47)$$

$$\ln \psi_t = \rho_\psi \ln \psi_{t-1} + (1-\rho_\psi)\ln \psi + \sigma_\psi \varepsilon_{\psi,t}, \quad \varepsilon_{\psi,t} \sim \mathcal{N}(0,1); \quad (48)$$

$$\ln \Theta_t = \rho_\Theta \ln \Theta_{t-1} + \sigma_\Theta \varepsilon_{\Theta,t}, \quad \varepsilon_{\Theta,t} \sim \mathcal{N}(0,1) \quad (49)$$

[6] We follow Schmitt-Grohé and Uribe (2003) in specifying the interest-rate premium.

3 Estimation

We can split the parameters of the model into two groups. The first group pins down the steady state of the model. We do not claim that we can empirically estimate the steady state that describes a potential-output equilibrium to which the Hungarian economy would converge in absence of shocks. The available Hungarian data are rather short, with several shocks that may be interpreted as structural breaks (such as the break-up of the Eastern Block, joining the EU, etc.). Instead, we calibrate this group of parameters so that the steady state of the model resembles the Hungarian economy between 2014Q1 and 2019Q4. This recent period of relative tranquility between the European Sovereign Debt Crisis and the Covid-19 Pandemic, when a comprehensive macroprudential framework was introduced in Hungary by the central bank, seems to be a good benchmark for the analysis of current issues.

The second group of parameters does not affect the steady state, but it does affect the dynamic behavior of the model. To estimate these parameters, we match the impulse-responses of the model with the empirical impulse-responses that we estimate from the Hungarian data. In particular, we focus on the first wave of the Covid-19 Pandemic: we estimate the Covid-19 shock from the data, and we set the dynamic parameters so that the model can replicate this shock.

In order to estimate the model's parameters, we introduce additional variables that relate the model to the data. For calibration, we need to define the nominal GDP:

$$GDP_t = P_t C_t + P_t I_t + \delta_H \bar{H} Q_{H,t} + \gamma Y_t P_{Y,t} + P_{X,t} X_t - P_{M,t} M_t. \tag{50}$$

The real GDP is then equal to GDP_t/P_t. The data set used for VAR estimation contains real investment, exports, house price index, and the rate of inflation. The real investment is simply I_t; the real exports are equal to $X_t P_{X,t}/P_t$; the real house price index is equal to $Q_{H,t}/P_t$. In the data, the rate of inflation is the rate of change in prices over the last four quarters, which corresponds to

$$INFL_t = \frac{P_t}{P_{t-4}} - 1. \tag{51}$$

3.1 CALIBRATION

The steady state of the model is calibrated to describe the Hungarian economy between 2014Q1 and 2019Q4. Table 1 demonstrates that we have aligned the model with its empirical targets quite well, and Table 3 in Section C of the Appendix lists all the calibrated parameter values.

We choose $R_t = 1.00224$, which corresponds to the annualized deposit interest rate of 0.9 percent, which is the central bank's policy rate before 2020. The discount factors $\beta = 0.995$ and $\hat{\beta} = 0.984$ help us pin down the stock of capital and mortgages relative to GDP. We set the utility weight of housing $\psi_{SS} = 0.23$ and the utility weight of deposits $\theta = 0.14$ to match the value of housing stock and deposits relative to GDP. In addition to other parameters such as discount factors, volatility of idiosyncratic credit shocks ($\sigma_H = 0.25$ and $\sigma_K = 0.3$) and borrower losses given default ($\mu_H = 0.1$ and $\mu_k = 0.1$) yield the interest rates for the two types of loans around 3.5 percent per year in the model, as well as the default rates around 0.5 percent. We set the number of impatient households $\Psi = 0.2$ to reflect the fact that roughly 15 percent of Hungarian households had mortgage loans during the reference period. We set borrowers' productivity $\kappa = 1.2$, which puts their wage 20 percent above the wage of the other households. Data from the Credit Registry suggests that mortgage borrowers do earn considerably more.

To reflect the macroprudential rules that apply to most borrowers, we put loan-to-value and debt-service-to-income caps at $g_{LTV} = 0.8$ and $g_{DSTI} = 0.5$, respectively. For the banks, we fix the minimum capital requirement at $g = 0.1$. As we target the value of mortgages and housing stock relative to GDP and adjust the average wage income of the borrowers, the model matches both the average LTV and DSTI from the credit-registry data. Using the same data, we also estimate the counter-factual borrower distribution with respect to LTV and DSTI that would have existed without LTV and DSTI caps, and find the proportion

Table 1
Steady-state values

Name	Target	Model
Consumption to GDP	62.0	63.8
Capital investment to GDP	18.0	17.5
Residential investment to GDP	3.0	4.2
Government spending to GDP	10.0	9.9
Exports to GDP	87.0	80.6
Imports to GDP	80.0	76.0
Capital stock to GDP	216.0	190.6
Housing stock to GDP	199.0	208.8
Labor share, non-tradables	65.0	59.1
Labor share, export sector	40.0	40.0
Deposit rate	0.9	0.9
Mortgage rate	4.5	3.5
Corporate loan rate	3.8	3.6
Mortgages to GDP	10.0	9.5
Bank equity to assets	14.8	14.2
Pr(bank undercapitalization)	1.0	1.6
Mortgage default rate	0.4	0.5
Corporate default rate	0.4	0.6
Average DSTI	26.7	23.9
Constrained by DSTI	1.0	1.0
Average LTV	52.3	51.4
Constrained by LTV	4.5	4.7
External debt to GDP	65.0	64.8
Annual inflation	3.0	3.4

The target values are computed on the yearly basis for the reference period 2014Q1–2019Q4 using data from the Central Statistical Office, the National Bank of Hungary, credit registry, and banks' financial statements. All the values are in percent.

of the borrowers that are constrained. We match these proportions in the model, where these proportions are defined as $\Phi(\tilde{\omega}_{LTV})$ and $\Phi(\tilde{\omega}_{DSTI})$, and largely determined by the volatility of idiosyncratic shocks ($\sigma_H = 0.25$ and $\sigma_W = 0.3$) and the cost of violating these limits ($\tau_{DSTI} = 0.02$ and $\tau_{LTV} = 0.02$).[7] During the reference period of 2014–2019, Hungarian banks held sizable capital buffers. The dividend payout ratio $\delta_B = 0.03$ helps match the average capital adequacy ratio, and the parameters related to the bank's non-compliance with the minimum capital requirement ($\sigma_B = 0.025$ and $\tau_B = 0.02$) yield the probability of a bank being under-capitalized of 1.6 percent.

The capital share $\alpha_Y = 0.35$ in the non-tradable sector, together with the mark-up parameter $\nu = 11$, jointly define the income share paid for labor equal to 0.59. For the tradable sector, we choose $\alpha_Z = 0.6$, which reflects the fact that the export sector is much more capital-intensive. The capital shares and the capital depreciation rate $\delta_K = 0.023$ largely define the share of capital investment in GDP. We set housing depreciation rate $\delta_H = 0.05$ to match the observed share of residential investment in GDP. The shares of imports in re-exports and in the domestically consumed final good, $\alpha_X = 0.6$ and $\alpha_F = 0.55$, together with elasticity of substitution $\nu_F = 2$, help us bring the model close to matching the empirical values of exports and imports

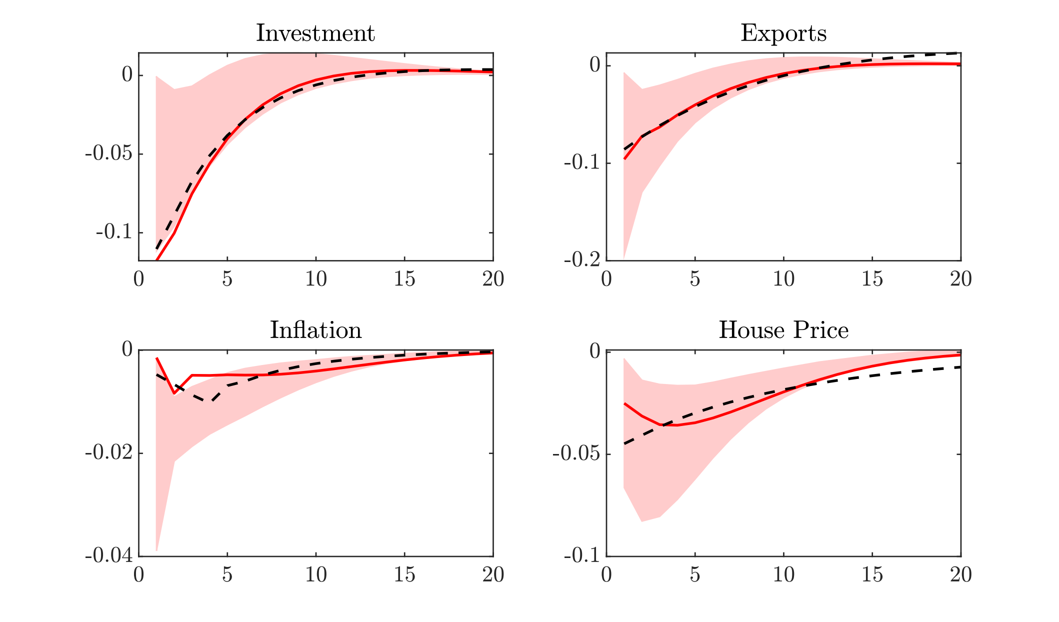
[7] It would be interesting to exploit the time-variation in the empirical LTV and DSTI ratios to estimate the model, but such time series are not available for Hungary; LTV and DSTI data are a recent addition to the credit registry.

relative to GDP. For the euro area during the reference period, we fix $R^* = 1.00125$, which corresponds to the interest rate of 50 basis points per year.

3.2 IMPULSE-RESPONSE MATCHING

Parameters $\{\phi, \xi_Y, \xi_X, \rho_y, \sigma_Y, \rho_\Theta, \sigma_\Theta, \rho_\psi, \sigma_\psi\}$ define the adjustment costs and the exogenous shock processes; they have no effect on the steady state. We identify them by matching the impulse-responses simulated by the model and estimated from the data. We find the parameter values that minimize the distance between the empirical and theoretical impulse-responses, which is a variation of the approach implemented by Bilbiie et al. (2008) and Christiano et al. (2005), among others. In our application, we want the model to be able to replicate the effect of the first wave of the Covid-19 Pandemic, which started in the first quarter of 2020.

Figure 2
The impact of the Covid-19 shock



The impulse-responses are estimated using 1996Q1–2020Q2 data. The shaded regions capture 90 percent of the IRFs that satisfy the sign restrictions; the red solid lines show the estimated IRF that falls closest to the data from the first two quarters of 2020; the black dashed lines show the impulse-responses generated by the model.

Empirically, we estimate a VAR model over the Hungarian data between 1996Q1 and 2020Q2. The data include real investment, real exports, inflation measured as the growth rate of the GDP deflator over the last four quarters, and the nominal house price index divided by the GDP deflator.[8] First, we use the data up to the end of 2019 in order to make a forecast for 2020. Then, we make an assumption that all the deviations from the forecast that we have observed in the first two quarters of 2020 are due to the first wave of the Covid-19 Pandemic. Of course there is a plethora of other factors that could have affected the data during that period, but we assume them to be relatively insignificant. We see that all the four variables in our data set fell well below the forecast by the second quarter of 2020. We use this information to impose the sign restrictions and identify the Covid-19 shock. We then estimate the SVAR and select random combinations of the 'structural' shocks that generate the impulse-responses that fit the sign restrictions, as prescribed by the literature (e.g., Fry and Pagan, 2011). Among those impulse-responses, we select the one closest (up to a constant of proportionality) to the unforeseen behavior of the data in the first half of 2020. Note that we try to match the unforeseen dynamics observed in two quarters only, yet we use the entire data set to estimate the shape of the matching impulse-response profile. Let $\hat{\varsigma}$ denote the impulse-response that we have empirically identified and selected to be representative of the Covid-19 shock in Hungary.

[8] The house price index was obtained from the National Bank of Hungary, the rest of the data were obtained from the Hungarian Central Statistical Office

Figure 2 shows 90 percent of the randomly generated impulse-responses that fit the sign restrictions corresponding to the Covid-19 shock, and highlights the impulse-response $\hat{\varsigma}$ that we have selected as the closest to the observed data. According to these estimates, the pandemic has caused a sharp fall of real activity in Hungary compared to the end-of-2019 forecast: investment and exports went down by about 10 percent. Inflation has decreased by 0.85 percentage point by the end of the second quarter, and its response is expected to remain within this limit. The real house price index is projected to fall by about 3–4 percent, peaking at the end of 2020, four quarters upon the shock. All of these estimates seem very reasonable.

Table 2
Estimated parameters

Symbol	Name	Value
ϕ	Capital adjustment cost	4
ξ_Y	Price-adjustment cost, non-tradables	10
ξ_X	Export-adjustment cost	20
ρ_Y	Labor-augmenting tech. AR coefficient	0.820
σ_Y	Labor-augmenting tech. shock st. deviation	0.088
ρ_Θ	Terms of trade AR coefficient	0.863
σ_Θ	Terms of trade shock st. deviation	0.130
ρ_ψ	Housing demand AR coefficient	0.927
σ_ψ	Housing demand shock st. deviation	0.276

Theoretically, we model the Covid-19 shock as a combination of all the model's three shocks that hit the economy simultaneously. Given parameterization θ, let $\varsigma(\theta)$ denote the corresponding impulse-response of the model to the shocks. For the group of parameters that we have selected for identification by means of IRF-matching, we run numerical optimization to find the values that minimize the following objective:

$$(\hat{\varsigma} - \varsigma(\theta))' U^{-1} (\hat{\varsigma} - \varsigma(\theta))$$

Essentially, we select parameters θ so that the squared distance between the empirical and the theoretical impulse-responses is minimized. The diagonal matrix U contains weights derived from the volatility of empirical responses of the four variables. The resulting estimates are reported in Table 2: the Covid-19 shock is replicated in the model as a combination of negative volatile but transitory shocks. Here, we would like to point out that a linear approximation to the solution of the model would be an inferior approach to compute the theoretical impulse-responses to such volatile shocks. We have computed the theoretical impulse-responses with non-linear methods and reported them in Figure 2 for comparison: overall, the model seems to replicate the responses quite well. The response of the variables measuring real activity fits the empirical profile almost perfectly, whereas the theoretical response of inflation seems delayed and the response of the house-price is not hump-shaped.[9]

[9] It takes inflation simulated by the model 4 quarters to reach its minimum after the shock because it is the annual inflation rate compounded of the last four quarterly inflation rates. For the house price, it is notoriously difficult to generate protracted response in a DSGE model - see, for example, Iacoviello and Neri (2010), Lozej et al. (2018), Rots (2017).

4 Results

4.1 CHANGES IN MACROPRUDENTIAL CONSTRAINTS

In the initial steady state, the regulatory borrowing caps are set at 80 percent for LTV and 50 percent for DSTI. Because these constraints are soft, both of them have an impact on the borrowing household. Consider first what happens when the macroprudential authority lowers the LTV cap from 80 to 76 percent. Figure 3 shows the effects of such a tightening. LTV cap has become tighter by 5 percent, which limits the borrowers' capacity to finance their housing purchases, so their housing and borrowing permanently decrease by comparable fractions. As a result, the house price falls, but only by 0.5 percent. The borrowers become less leveraged, so that the mortgages are less risky: the mortgage default rate falls, together with the mortgage interest rate. Due to the fall in mortgage lending, the banks become less leveraged, which makes them less profitable. Lower mortgage interest does not help either. The banks cannot quickly reduce the equity; instead, they respond by offering more corporate loans at lower rates. The entrepreneurs take up the possibility to borrow at low cost and increase capital investment, but only marginally. The effect on GDP is minimal: it slightly falls, mainly because lower house prices decrease the value of the residential investment. Overall, the spillovers are rather small even to the housing market, let alone the rest of the economy, and the effect of a change in LTV caps is mainly on the market for mortgages.

Figure 3
The impact from changes in LTV and DSTI caps

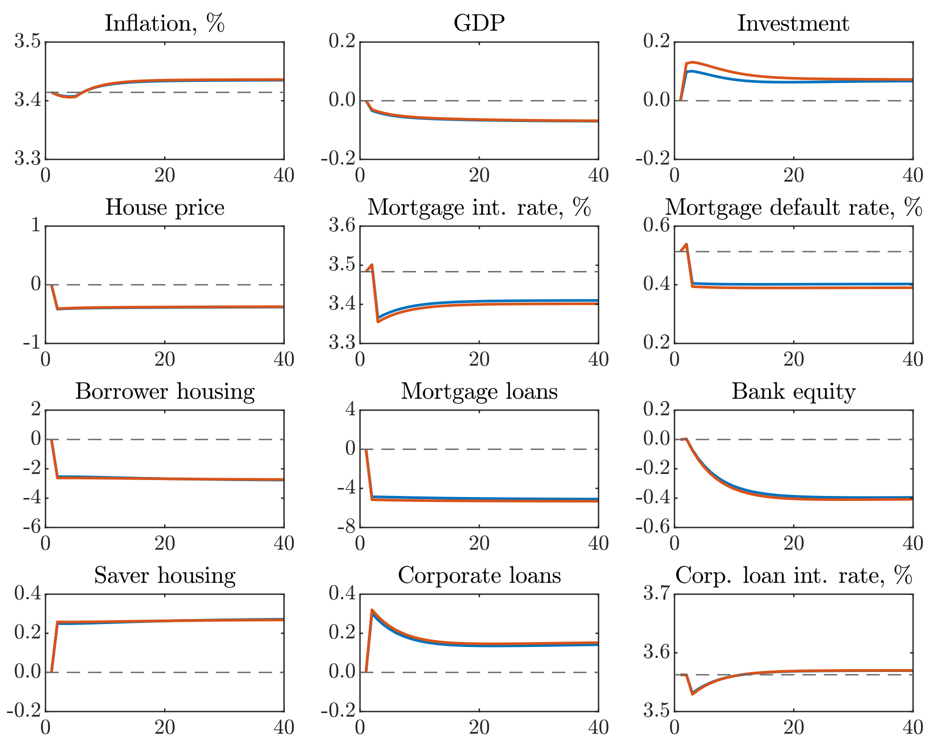
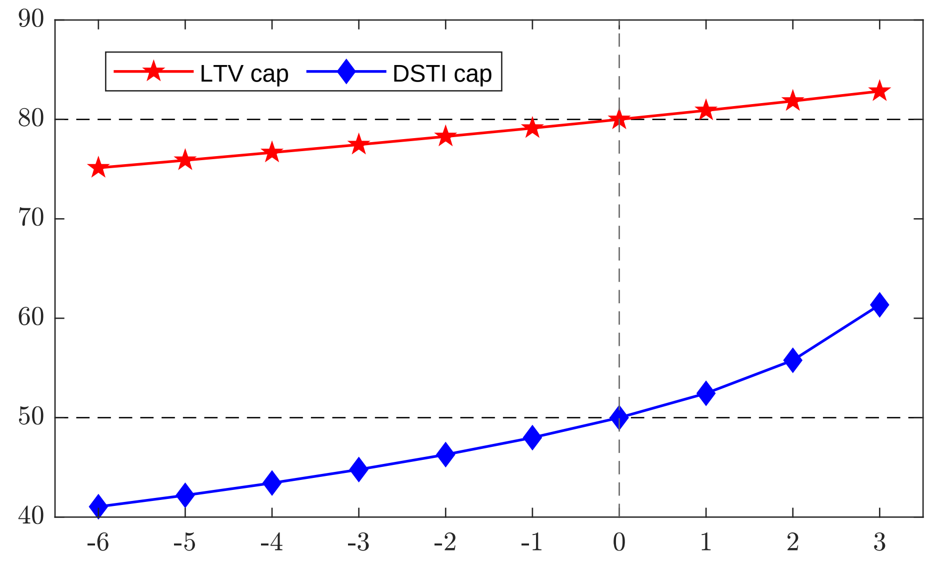


Figure shows the impact of LTV going from 80 to 76 percent (blue lines) and DSTI going from 50 to 42 percent (orange lines). All the interest rates and the inflation rates are in percentage points per year. The default rates are in percentage points per quarter. All the other variables are in percentage-point deviations from the initial steady state. Black dashed lines indicate the initial levels.

A similar effect can be achieved by a decrease in the DSTI limit. Figure 3 plots the effect of the decrease from 50 to 42 percent. It can be seen that this policy change essentially has the same impact, both qualitatively and quantitatively. The same finding is reported by Lozej, Rannenberg, et al. (2017) for a similar model.[10] We do want to add, however, that we have calibrated the model so that it matches the average LTV and DSTI ratios, as well as the fractions of borrowers that seem constrained by the two caps. Based on the bunching observed in the credit-registry data, we can say that the LTV cap has been affecting a larger fraction of the mortgage borrowers. For the reference period, we see that the empirical mean LTV ratio is about two-thirds of the LTV cap, and we find roughly 4.5 percent of the borrowers bunching near the cap. In the model, we match the average LTV ratio, and set it so that 4.7 percent of the borrowers find their optimal loan exceeding the LTV cap. As the LTV cap affects a sizable portion of the population, we see that a reduction of the cap from 80 to 76 percent would cause a large disruption in the market for mortgages, and a noticeable effect on the housing market. The DSTI cap seems to be far less important during the reference period, because the average DSTI ratio is roughly two times less than the cap, and only 1–2 percent of the borrowers find themselves constrained by the cap. To have a comparable impact with the reduction of the LTV cap from 80 to 76 percent (by 5 percent), the regulator needs a much larger reduction of the DSTI cap, from 50 percent to 42 percent (by 16 percent), according to our estimates.

Figure 4
Changes in borrowing caps and changes in mortgage lending



The horizontal axis measures percentage-point deviation of the stock of mortgages from the initial steady state one quarter after the regulatory change in the cap, and the vertical axis measures the corresponding value for LTV or DSTI cap. For example, to make mortgage lending fall by 1 p.p. within one quarter, the regulator has to decrease LTV cap from 80 to 79.1 percent, or decrease DSTI cap from 50 to 48.0 percent.

To make the comparison clearer, we have computed for each borrowing cap the new value that the regulator would have to implement in order to achieve a certain percentage deviation of the mortgage lending from the initial steady state one quarter after the regulatory change and plotted it in Figure 4. The figure confirms that the DSTI cap is less effective than the LTV cap in the market setting of the reference period. This is especially true if the task is to set a looser credit-market environment: because few borrowers are constrained by the DSTI cap anyway, raising it has little impact. Note also that the schedules that we have plotted are non-linear and highly asymmetric around the steady state. This would be impossible to have if we relied on linear approximation to the solution of the model. As macroprudential policy often deals with tail risks and other non-linear features of the credit market, we concur with the argument against linearized models.

Finally, Figure 5 shows the impact of the minimum capital requirement permanently raised from 10 to 11 percent. This example is a good opportunity to discuss the behavior of bank equity. Higher capital requirement translates into higher risk that a bank faces under-capitalization and incurs its costs, as equation (2) demonstrates. In other words, banks suddenly find themselves over-leveraged. Yet, they cannot quickly adjust their equity due to high adjustment costs. At the same time, the

[10] Lozej, Rannenberg, et al. (2017) report qualitatively similar impulse-responses; however, they find a sizable negative impact of tighter borrowing caps on capital investment, because in their model, the same households borrow mortgages and invest into capital. As the authors correctly predict, in a model like ours, where these agents are separated, the large spillover vanishes.

Figure 5
The impact from an increase in the minimum capital requirement

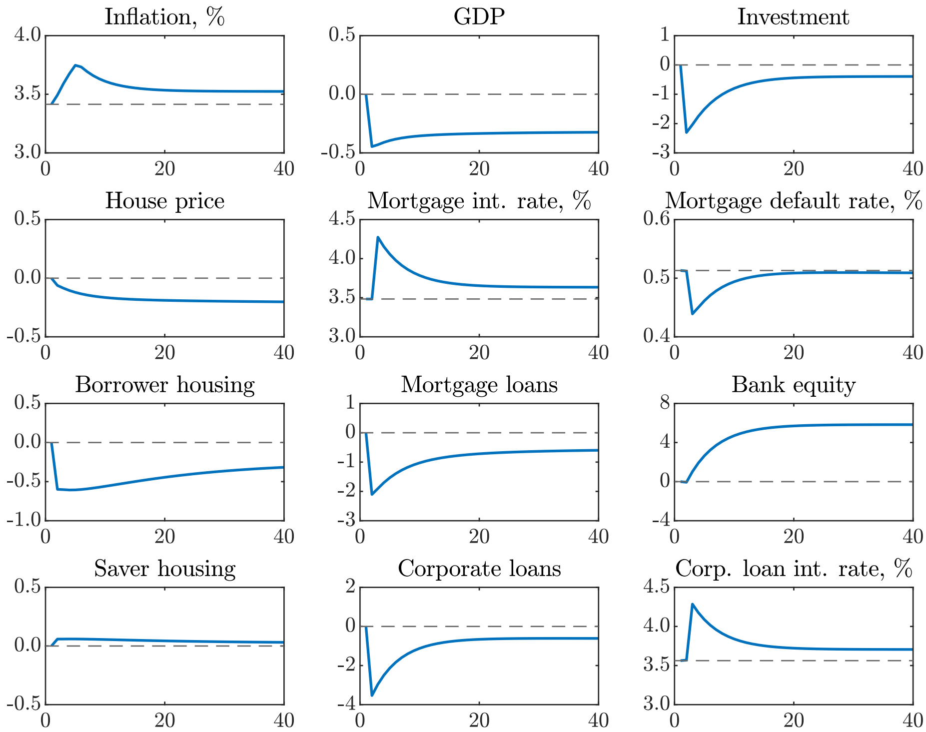


Figure shows the impact of the minimum capital requirement going from 10 to 11 percent. All the interest rates and the inflation rates are in percentage points per year. The default rates are in percentage points per quarter. All the other variables are in percentage-point deviations from the initial steady state. Black dashed lines indicate the initial levels.

bank's balance-sheet identity (1) suggests that for a fixed amount of equity, a reduction in the stock of loans must come with a reduction in deposits by the same amount. Going back to equation (2), if banks reduce both loans and deposits by the same amount, they reduce the chance of under-capitalization.[11] Therefore, to manage the increased risk, banks respond by cutting the supply of loans. As a result, both mortgage and corporate lending falls, whereas the interest rates increase. The short-run impact of less lending is that the interest rate spreads increase, which makes it lucrative for the banks to increase the scope of lending, provided that they can maintain sufficient capital adequacy ratio. The way to do so is to build up equity. Gradually, banks do recapitalize: equity increases, together with the amount of extended loans. However, re-capitalization does not fully compensate for the increase in the minimum capital requirement (the requirement increases by 10 percent, whereas the banks eventually increase the equity by about 6 percent). Thus, there is a permanent reduction in the scope of lending, by about 1 percent for both types of loans. Importantly, because we assume that banks can adjust equity, we can see that the banking sector can gradually recover the scope of lending, at least partially.[12] It is also important to note that, compared to changes in DSTI and LTV caps, the impact of a change in the minimum capital requirement is broader. It is not only the mortgages that are affected, but also the corporate loans; consequently, there is a significant impact on investment and GDP, especially in the short run.

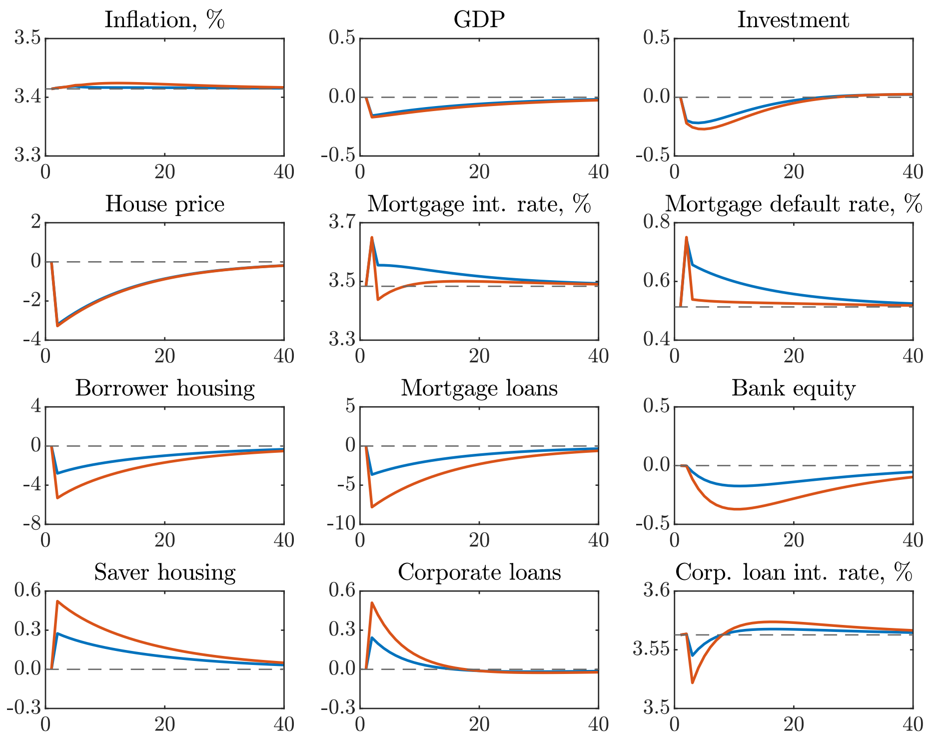
[11] This is straighforward to show, given that $D + \Psi\hat{D} < L_E + \Psi\hat{L}_H$ and $R_E > R$ and $R_H > R$, meaning that equity and interest spreads are positive.

[12] In our experiments, when we assumed lower adjustment costs for bank equity, the equity would build up and the scope of lending would recover faster, but the recovery would remain partial.

4.2 HOUSING DEMAND SHOCK AND MACROPRUDENTIAL SUPPORT

Figure 6 demonstrates the effects of a negative shock to the weight of housing ψ_t in the utility function. This is a negative housing demand shock of the same magnitude as we have estimated in order to replicate the effect of the first wave of the Covid-19 Pandemic: the result is that the house price goes down by 3 percent. In the first period upon the shock, the mortgage default rate spikes up, because the unexpected house price decline drives the value of the house below the value of outstanding debt for many borrowers. The banks increase the mortgage rate momentarily in order to compensate for the higher default rate and secure the return on mortgage lending that they have been expecting before the shock. Both the default rate and the mortgage interest rate go back down in the next quarter, since there are no further unexpected movements in the housing market. Due to the shock, the borrowers reduce their demand for housing and mortgages. This reduction is extended by the fact that the value of borrowers' collateral falls, which means that they have less access to mortgage financing. The combined effect is that borrowers' housing purchases fall dramatically by 5 percent, whereas mortgage borrowing falls by 8 percent. Banks face a dramatic collapse of mortgage lending and therefore find themselves with leverage below the optimal. They respond by offering more corporate loans at a lower interest. The patient households take the offer, but still their capital investment slightly falls because they substitute it for housing stock, which has become more accessible as well. GDP falls slightly, mostly due to lower residential and capital investment. Importantly, housing is redistributed to patient households: their demand is also lower, but they buy up the housing stock because it has become cheaper. Note that they do not use housing as collateral and do not have leveraged holdings of the housing stock. So, cheaper housing allows patient households to have more of it, while it constrains borrowers' access to mortgages and therefore their ability to buy housing.

Figure 6
The impact from a negative shock to the preferences for housing



The interest rates and the inflation rate are in percentage points per year. The default rates are in percentage points per quarter. All the other variables are in percentage-point deviations from the initial steady state. Black dashed lines indicate the initial levels. Red lines show the impact of the housing-demand shock; blue lines show the same shock accompanied by the supportive macroprudential policy to raise the LTV cap.

The borrowers seem to be vulnerable in case of such a housing-market event: they lose home equity, and they have to sell housing stock. To support the mortgage market in such a scenario, the macroprudential authority may consider relaxing some of its regulatory limits. After all, protection of the financial stability in a scenario like this is one of the main reasons behind the introduction of a comprehensive macroprudential framework in many countries, including Hungary, after the Global Financial Crisis of 2007–2009, which came with a housing-market bust in many economies. To see the effect of macroprudential support, let us consider the regulator that sets the borrowing caps depending on the gap between the house price and its steady-state level. In this exercise, we follow the literature that discusses rules for the macroprudential policy leaning against the financial cycles, such as Lambertini et al. (2013), Clerc et al. (2015), Lozej, Rannenberg, et al. (2017), etc. We focus only on the LTV cap, because we have shown it to be more effective than the DSTI cap, and we introduce the following rule:

$$g_{LTV,t} = 0.80 + (\bar{q}_H - q_{H,t}) * \eta_{LTV},$$

where $\bar{q}_H$ is the steady-state real house price index, $q_{h,t}$ is current real house price index, and $\eta_{LTV} = 0.05$ is the sensitivity of the LTV cap to the house-price gap. We do not say that this rule is in any way realistic: it requires that the macroprudential authority knows the steady-state real house price and adjusts the LTV cap every quarter in a timely manner. We use this rule only to say what happens when the authority steps in to provide support to the borrowers in the form of looser lending standards. In Figure 6, we see that this policy can mitigate the impact of the shock: the borrowers still lose home equity, but their access to mortgages is propped up by the higher LTV cap. As a result, borrowers' housing-stock losses are halved. Note, however, that the mortgage default rate and the interest rate remain elevated as long as the borrowers are offered looser lending standards.

We have established that macroprudential policy can effectively support the credit market and mitigate the losses of the borrowers in case of a disruption, although there are three caveats to mention. First, such support comes with additional credit risk, as the elevated mortgage default rates show in Figure 6. Second, this policy has little impact on the house price or any other sector of the economy other than the credit market. This applies to economies like Hungary, where the mortgage market is small: only 15 percent of households have mortgages, and the stock of mortgages is less than 10 percent of the annual GDP. And third, an efficient macroprudential policy would require proper timing and scaling of its policies, which we have assumed by introducing the rule, and which is much more difficult to achieve in reality.

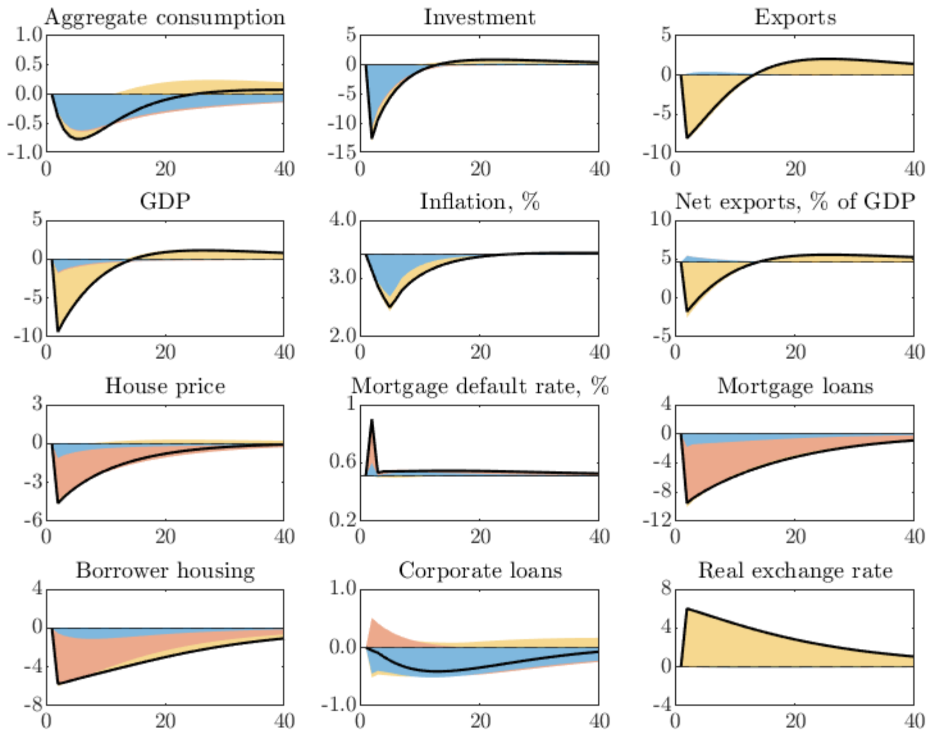
4.3 THE EFFECT OF THE FIRST WAVE OF THE COVID-19 PANDEMIC

We model the Covid-19 shock as a combination of three simultaneous shocks, and we show in Figure 7 how the Covid-19 shock is decomposed into its three components.

The first shock is the negative shock to labor-augmenting technology in the non-tradable sector, which can be interpreted as the lockdown that has hindered real activity and lowered incomes, especially for the workers of service industries. This is a typical productivity shock that is responsible for the decline in aggregate consumption and capital investment (e.g., Smets and Wouters, 2003). Low profitability prospects for capital investment also explain why corporate lending falls. There are three interesting features that we should point out. First, inflation falls upon this shock, contrary to what might be expected from a productivity shock (e.g., Ireland, 2004). It could be the case that the fall in household income from the non-tradable sector causes a large fall in aggregate demand, which results in lower inflation. For example, Guerrieri et al. (2020), motivated by the evidence from the Pandemic, argue that a supply shock can potentially provoke an even larger response of the demand in a multi-sector economy and therefore be deflationary. Second, the spillovers from this shock to the housing market are rather moderate: lower household income does cause the housing demand to fall, but the response of the house price is not as large as observed in the data. If we did not include the house price index into our data set for the VAR estimation, we could do without the housing-demand shock. However, the focus of the model is macroprudential regulation, so we have included the house price index into the data in order to account for the behavior of the housing and the mortgage market during the Pandemic. That is why the housing-demand shock plays an important role. Finally, a productivity shock typically creates counter-cyclical response of net exports, which is the standard result in the RBC literature (e.g., Backus et al., 1992). Indeed we see that net exports increase due to the productivity shock, mainly because the demand for imports falls. The terms-of-trade shock helps simulate the fall in net exports in order to replicate the impact of the Pandemic.

The second shock is the negative housing demand shock, which we have covered in Section 4.2. The decomposition confirms that its impact is contained within the housing and the credit market. Technically, it helps simulate the decrease in the house price that is large enough to match the data. Intuitively, we can use this result to argue that the lockdown measures and the associated fall in incomes are only one part of the reason behind the decline of the housing market. Indeed, there have been additional factors. Namely, real estate investment has become far less profitable in Hungary in 2020. Budapest has become less

Figure 7
The effect of the Covid-19 Crisis



The interest rates and the inflation rate are in percentage points per year. The default rates are in percentage points per quarter. Net exports are in percent of steady-state (pre-shock) GDP. All the other variables are in percentage-point deviations from the initial steady state. Thick black lines indicate the responses; thin horizontal black lines show the initial levels. Blue shade shows the contribution of the labor-productivity shock; red shade shows the contribution of the housing demand shock; yellow shade shows the contribution of the terms-of-trade shock. Investment, exports, inflation, and house price responses correspond to the ones plotted in Figure 2

attractive in particular, first, because of the legislation passed in the summer of 2020 that restricted AirBnB rentals, and second, because of the border closures that prevented the tourists from visiting the capital city and added damage to the market for short-term rentals. According to the National Bank of Hungary,[13] Budapest is the only market experiencing falling house prices in 2020; and the fraction of home buyers for investment purposes went from 40–50 percent in 2019 down to 30 percent in 2020. In addition, there had been a housing boom in Hungary for several years prior to 2020, with real house prices doubling in Budapest since 2014, so that there was a growing concern by 2020 that the market was overvalued. The housing market had been slowing down even before the Pandemic, according to the house-price data. Taking all these factors into consideration, introducing an additional housing-demand shock seems reasonable.

The third shock is a temporary decline in the terms of trade, which represents the decline in export demand. Needless to say, the Pandemic has affected every economy around the world, including the Euro Area, Hungary's main trading partner. With the terms-of-trade shock, the model is able to replicate the decline in exports and to capture the fact that net exports became negative during the first half of 2020. The fall in net exports is responsible for most of the decline of the GDP estimated by the model, which is in line with the data. We estimate up to 10-percent decline in real quarterly GDP due to the Covid-19 shock, which is short of the official estimate of 14 percent for the second quarter of 2020. Note that GDP is not a part of the data used for the estimation.[14] The decrease in export demand also causes the real exchange rate to increase by 6 percent. During the Pandemic, the Hungarian forint has depreciated against the euro, and the exchange rate increased from 330 forints per euro at

[13] MNB Housing Market Report, November 2020

[14] We under-estimate the fall in GDP because the consumption response is too small in out model. We can probably achieve a larger response in consumption and a better fit of the model if we account for durable consumption in the model.

the end of 2019 up to an average of 360 in the second quarter of 2020, which is a 7.5 percentage increase in the real exchange rate, according to our back-of-the-envelope calculations. The additional depreciation of the national currency that we see in the data is due to easing of the monetary policy during the crisis and due to the prevalence of the ”risk-off” investor sentiment, as many investment banks have pointed out in their reports.

Overall, we are satisfied with the fit of the model and its ability to make sense of the economy's performance during the crisis by decomposing it into three key factors: a fall in incomes due to lockdown measures, a fall in export demand, and a fall in the demand for housing.

In order to extend the presented analysis and find implications for the macroprudential policy during this difficult period, we have to keep in mind that some policy measures have already been implemented, and they have affected the data that we are trying to replicate with the model. The Covid-19 crisis was not caused by a disruption of the financial market, and there were no obvious prior credit-market imbalances to address, unlike in the case of the Global Financial Crisis, which motivated the establishment of the macroprudential policy framework. The key driver of the crisis is a reduction in real activity induced by government policies to control the spread of the disease. Therefore, macroprudential policy is validated inasmuch as it can help mitigate the impact of the crisis on the credit market and have positive spillovers to the real side of the economy.

Borrower-based measures, such as increasing the LTV or the DSTI cap, could be used to support the mortgage market and prop up the deteriorating housing market. However, the mortgage market was not over-heated prior to the crisis: for the reference period, we have estimated that only 4.5 percent of the borrowers were constrained by the LTV cap and 1–2 percent by the DSTI cap. Higher caps would be a support for a small fraction of the borrowers, and, as we have shown in Section 4.1, their effect would be limited to the housing and the mortgage market. On the contrary, we support the moratorium on loan repayment implemented by the National Bank of Hungary in March 2020,[15] as it is a much more broad-based measure. It alleviates the problem of mortgage defaults, which would have doubled without the moratorium according to our estimates (see Figure 7). In addition, it frees up liquidity that many households could use in the face of falling income and therefore supports the aggregate demand. Relaxing the minimum capital requirements is another welcomed policy, because it has a broad effect.[16] It increases the banks' supply of loans and helps mitigate the impact of the crisis on the housing market and also combat the decline in capital investment, as we have shown in Section 4.1.

[15] Starting April 2020, households were released of the obligation to repay their existing loans until the end of 2020. The loan repayment schedule shifted by 9 months, so that the payments would resume in January 2021. At the end of 2020, the moratorium was extended until July 2021. All the interest accrued during the moratorium would have to be repaid in form of additional loan payments after the end of the term of the loan contract. Borrowers had an option to opt out of the moratorium and keep repaying.

[16] For example, the National Bank of Hungary refrained from prescribing the maintenance of systemic risk buffers and additional buffers for systemically important institutions in 2020.

5 Conclusion

Our goal is to build a general-equilibrium model that can be used to provide recommendations concerning the conduct of macroprudential policy in Hungary. To that end, we have taken several steps that are beyond the path typically taken in the related literature. First, we introduce the loan-to-value and debt-service-to-income caps in a novel way as soft constraints, which allows us to to analyze the macroprudential framework with several borrowing limits. Second, we design the banking sector following Benes et al. (2014) and assume that banks actively manage the optimal size of their balance sheets. Because of this assumption, our model reflects the fact that credit markets can be volatile and sensitive to shocks, which in reality provides additional scope for macroprudential policy. Third, we have chosen a specific approach to estimate the model, which gives a lot of weight to the most recent data. We realize that this tactic raises the issue of over-identification; yet, we stick to it because we do not have much data concerning the conduct of macroprudential policy in Hungary, and because we want to comment on the pressing issue, which is the Covid-19 Crisis. We argue that our modeling and estimation decisions are justified given the task at hand and the available data (or the lack of it).

Our model has its limitations, of course. There is an issue of over-identification, as we have mentioned. The model would benefit from validation, so additional empirical evidence related to macroprudential policy in Hungary would be valuable. There is space for improvement in the design of the model as well. For example, we could consider a design with mortgage loans that last longer than one quarter in the model, as it is done by Chatterjee and Eyigungor (2015).

Despite these limitations, we have developed a medium-scale DSGE model that produces intuitive results. It can help evaluate counter-factual scenarios, novel policies, and other potential events that cannot be supported by the existing data. It can be used to analyze and develop recommendations concerning macroprudential policies and their potential effects on the credit market, the housing market, and the rest of the economy.

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Appendix A Additional Equations to Close the Model

In addition to equations (1)–(49), let us write down all the missing equations to describe the complete model. Note that $\hat{\Lambda}_{H,t}$ and $\Lambda_{E,t}$ are the Lagrange multipliers that correspond to bank participation constraints (17) and (19) in the household optimization problems.

A.1 IMPATIENT HOUSEHOLDS

$$G'_{H,t} = \frac{\phi(z_{H,t})}{\sigma_W}; \tag{52}$$

$$\Gamma'_{H,t} = 1 - \Phi(z_{H,t}); \tag{53}$$

$$\hat{\Lambda}_t P_t = \frac{1-\chi}{\hat{C}_t - \chi \hat{C}_{t-1}}; \tag{54}$$

$$\hat{\Lambda}_t = R_t \hat{\beta} \hat{\Lambda}_{t+1} + \frac{\theta}{P_t}\left(\frac{\hat{D}_t}{P_t}\right)^{-\iota}; \tag{55}$$

$$\begin{aligned}\hat{\Lambda}_t Q_{H,t}\hat{H}_t = {}& \psi_t + \hat{\Lambda}_{H,t} Q_{H,t+1}\hat{H}_t(1-\delta_H)(\Gamma_{H,t+1} - \mu_H G_{H,t+1} - \Gamma'_{H,t+1}\tilde{\omega}_{H,t+1} + \mu_H G'_{H,t+1}\tilde{\omega}_{H,t+1}) + \\ &+ \hat{\beta}\hat{\Lambda}_{t+1} Q_{H,t+1}\hat{H}_t(1-\delta_H)(1-\Gamma_{H,t+1} + \Gamma'_{H,t+1}\tilde{\omega}_{H,t+1});\end{aligned} \tag{56}$$

$$\begin{aligned}\hat{\Lambda}_{H,t} Q_{H,t+1}\hat{H}_t(1-\delta_H)(\Gamma'_{H,t+1} - \mu_H G'_{H,t+1})\tilde{\omega}_{H,t+1} = {}& \hat{\beta}\hat{\Lambda}_{t+1} Q_{H,t+1}\hat{H}_t(1-\delta_H)\Gamma'_{H,t+1}\tilde{\omega}_{H,t+1} + \\ &+ \hat{\beta}\hat{\Lambda}_{t+1}\hat{L}_{H,t}\tau_{LTV}\frac{\phi(z_{LTV,t+1})}{\sigma_H} + \hat{\beta}\hat{\Lambda}_{t+1}\hat{L}_{H,t}\tau_{DSTI}\frac{\phi(z_{DSTI,t+1})}{\sigma_W}\left(\frac{\tilde{R}_{H,t+1}}{\tilde{R}_{H,t+1}-1} - \frac{n\tilde{R}^{-n}_{H,t+1}}{1-\tilde{R}^{-n}_{H,t+1}}\right);\end{aligned} \tag{57}$$

$$\begin{aligned}\hat{\Lambda}_t\hat{L}_{H,t} + \hat{\Lambda}_{H,t} Q_{H,t+1}\hat{H}_t(1-\delta_H)(\Gamma'_{H,t+1} - \mu_H G'_{H,t+1})\tilde{\omega}_{H,t+1} = {}& \hat{\Lambda}_{H,t}\hat{L}_{H,t}R_{H,t} + \hat{\beta}\hat{\Lambda}_{t+1} Q_{H,t+1}\hat{H}_t(1-\delta_H)\Gamma'_{H,t+1}\tilde{\omega}_{H,t+1} + \\ &+ \hat{\beta}\hat{\Lambda}_{t+1}\hat{L}_{H,t}\left(\tau_{LTV}\Phi(z_{LTV,t+1}) + \tau_{DSTI}\Phi(z_{DSTI,t+1})\right) + \hat{\beta}\hat{\Lambda}_{t+1}\hat{L}_{H,t}\left(\tau_{LTV}\frac{\phi(z_{LTV,t+1})}{\sigma_H} + \tau_{DSTI}\frac{\phi(z_{DSTI,t+1})}{\sigma_W}\right).\end{aligned} \tag{58}$$

A.2 PATIENT HOUSEHOLDS

$$z_{K,t} = \frac{\ln(\tilde{\omega}_{K,t})}{\sigma_K} + \frac{\sigma_K}{2}; \tag{59}$$

$$G_{K,t} = \Phi(z_{K,t} - \sigma_K); \tag{60}$$

$$\Gamma_{K,t} = \Phi(z_{K,t} - \sigma_K) + \tilde{\omega}_{K,t}\big(1 - \Phi(z_{K,t})\big); \tag{61}$$

$$G'_{K,t} = \frac{\phi(z_{K,t})}{\sigma_K}; \tag{62}$$

$$\Gamma'_{K,t} = 1 - \Phi(z_{K,t}); \tag{63}$$

$$\Lambda_t P_t = \frac{1-\chi}{C_t - \chi C_{t-1}}; \tag{64}$$

$$\Lambda_t = R_t \beta \Lambda_{t+1} + \frac{\theta}{P_t}\left(\frac{D_t}{P_t}\right)^{-\iota}; \tag{65}$$

$$\Lambda_t Q_{H,t} H_t = \psi_t + \beta\Lambda_{t+1} Q_{H,t+1} H_t (1-\delta_H); \tag{66}$$

$$\Lambda_t = \beta\Lambda_{t+1} R_{K,t+1}(1-\Gamma_{K,t+1}) + \Lambda_{E,t} R_{K,t+1}(\Gamma_{K,t+1} - \mu_K G_{K,t+1}); \tag{67}$$

$$\beta\Lambda_{t+1}R_{K,t+1}\Gamma'_{K,t+1}\tilde{\omega}_{K,t+1} = \Lambda_{E,t}R_{K,t+1}(\Gamma'_{K,t+1} - \mu_K G'_{K,t+1})\tilde{\omega}_{K,t+1}; \tag{68}$$

$$\Lambda_t = \Lambda_{E,t}R_{E,t}; \tag{69}$$

$$\Pi_t = \delta_H \bar{H} Q_{H,t} + \Pi_{K,t} + \Pi_{Y,t} + E_{B,t-1}R_{B,t} - E_{B,t} + \left(L_{E,t-1} + \Psi\hat{L}_{H,t-1}\right)\tau_B\Phi(z_{B,t}). \tag{70}$$

A.3 PRODUCTION

$$\Pi_{Y,t} = P_{Y,t}Y_t\left(1 - \frac{\xi_Y}{2}\left(\frac{P_{Y,t}}{P_{Y,t-1}} - \frac{P_{Y,t-1}}{P_{Y,t-2}}\right)^2\right) - U_{Y,t}Y_t; \tag{71}$$

$$\Pi_{X,t} = P_{X,t}X_t\left(1 - \frac{\xi_X}{2}\left(\ln\frac{X_t}{X_{t-1}}\right)^2\right) - -\alpha_X P_{M,t}M_{X,t} - W_t N_{Z,t} - W_{K,t}K_Z; \tag{72}$$

$$M_t = M_{Y,t} + M_{X,t}. \tag{73}$$

Appendix B Solving the bank's optimization problem

This section provides a more detailed derivation of the bank's first-order conditions. Recall from Section 2 that the bank has the following maximization problem:

$$\max_{\{E_t, L_{E,t}, \hat{L}_{H,t}, D_t, \hat{D}_t\}} \mathbf{E}_t \left\{ \beta \frac{\Lambda_{t+1}}{\Lambda_t} \left[R_{E,t} L_{E,t} + R_{H,t} \Psi \hat{L}_{H,t} - R_t (D_t + \Psi \hat{D}_t) - \tau_B \Phi(z_{B,t+1})(L_{E,t} + \Psi \hat{L}_{H,t}) \right] \right\} - E_{B,t} - \frac{\xi_B}{2} \Omega_{B,t}^2 E_{B,t} \tag{74}$$

$$\text{s.t. } L_{E,t} + \Psi \hat{L}_{H,t} = E_{B,t} + D_t + \Psi \hat{D}_t; \tag{75}$$

$$z_{B,t} = \frac{\ln \tilde{\omega}_{B,t}}{\sigma_B} + \frac{\sigma_B}{2}; \tag{76}$$

$$\tilde{\omega}_{B,t} = \frac{(D_{t-1} + \Psi \hat{D}_{t-1}) R_{t-1}}{(1 - g_{t-1})(L_{E,t-1} R_{E,t-1} + \Psi \hat{L}_{H,t-1} R_{H,t-1})}; \tag{77}$$

$$\Omega_{B,t} = \ln \left(\frac{E_{B,t}}{E_{B,t-1} R_{B,t} (1 - \delta_B)} \right). \tag{78}$$

Let us treat the first constraint, the balance-sheet identity (75) as a separate constraint with Lagrange multiplier μ_t, and let us work the remaining three definitions for z_B, $\tilde{\omega}_B$, and Ω_B into our computations of the derivatives when we find the first-order conditions. The Lagrangian, therefore, is the following:

$$\mathcal{L} = \mathbf{E}_t \left\{ \beta \frac{\Lambda_{t+1}}{\Lambda_t} \left[R_{E,t} L_{E,t} + R_{H,t} \Psi \hat{L}_{H,t} - R_t (D_t + \Psi \hat{D}_t) - \tau_B \Phi(z_{B,t+1})(L_{E,t} + \Psi \hat{L}_{H,t}) \right] \right\} - \\ - E_{B,t} - \frac{\xi_B}{2} \Omega_{B,t}^2 E_{B,t} + \mu_t \left[E_{B,t} + D_t + \Psi \hat{D}_t - L_{E,t} - \Psi \hat{L}_{H,t} \right]. \tag{79}$$

Since we solve the model using the shooting method, which computes predetermined paths conditional on the initial unexpected shock, let us drop the expectation terms. The first-order conditions with respect to equity, deposits, and loans are the following:

$$E_{B,t}: \quad 1 + \frac{\xi_B}{2} \Omega_{B,t}^2 + \xi_B \Omega_{B,t} = \mu_t; \tag{80}$$

$$D_t,\ \hat{D}_t: \quad \mu_t = \beta \frac{\Lambda_{t+1}}{\Lambda_t} \left(R_t + \frac{\tau_B}{\sigma_B} \phi(z_{B,t+1}) \frac{L_{E,t} + \Psi \hat{L}_{H,t}}{D_t + \Psi \hat{D}_t} \right); \tag{81}$$

$$L_{E,t}: \quad \beta \frac{\Lambda_{t+1}}{\Lambda_t} \left(R_{E,t} - \tau_B \Phi(x_{B,t+1}) + \frac{\tau_B}{\sigma_B} \phi(z_{B,t+1}) \frac{R_{E,t}(L_{E,t} + \Psi \hat{L}_{H,t})}{L_{E,t} R_{E,t} + \Psi \hat{L}_{H,t} R_{H,t}} \right) = \mu_t; \tag{82}$$

$$\hat{L}_{H,t}: \quad \beta \frac{\Lambda_{t+1}}{\Lambda_t} \left(R_{H,t} - \tau_B \Phi(x_{B,t+1}) + \frac{\tau_B}{\sigma_B} \phi(z_{B,t+1}) \frac{R_{H,t}(L_{E,t} + \Psi \hat{L}_{H,t})}{L_{E,t} R_{E,t} + \Psi \hat{L}_{H,t} R_{H,t}} \right) = \mu_t. \tag{83}$$

If we substitute μ_t out of equations (82) and (83) using the first-order condition (81) for deposits, we get equations (9) and (10) reported in Section 2:

$$R_{E,t} - R_t = \mathbf{E}_t \left\{ \tau_B \Phi(z_{B,t+1}) + \frac{\tau_B}{\sigma_B} \phi(z_{B,t+1}) \left(L_{E,t} + \Psi \hat{L}_{H,t} \right) \times \left(\frac{1}{L_{E,t} + \Psi \hat{L}_{H,t} - E_{B,t}} - \frac{R_{E,t}}{L_{E,t} R_{E,t} + \Psi \hat{L}_{H,t} R_{H,t}} \right) \right\}; \tag{84}$$

$$R_{H,t} - R_t = \mathbf{E}_t \left\{ \tau_B \Phi(z_{B,t+1}) + \frac{\tau_B}{\sigma_B} \phi(z_{B,t+1}) \left(L_{E,t} + \Psi \hat{L}_{H,t} \right) \times \left(\frac{1}{L_{E,t} + \Psi \hat{L}_{H,t} - E_{B,t}} - \frac{R_{H,t}}{L_{E,t} R_{E,t} + \Psi \hat{L}_{H,t} R_{H,t}} \right) \right\}. \tag{85}$$

As for the first-order condition for equity, let us follow Benes et al. (2014) and start with equation (6) that defines the return on equity:

$$E_{B,t} R_{B,t+1} = R_{E,t} L_{E,t} + R_{H,t} \Psi \hat{L}_{H,t} - R_t \left(D_t + \Psi \hat{D}_t \right) - \tau_B \Phi(z_{B,t+1}) \left(L_{E,t} + \Psi \hat{L}_{H,t} \right).$$

Let us use the bank's balance-sheet identity (75) to replace the deposits:

$$E_{B,t} R_{B,t+1} = (R_{E,t} - R_t) L_{E,t} + (R_{H,t} - R_t) \Psi \hat{L}_{H,t} + R_t E_{B,t} - \tau_B \Phi(z_{B,t+1}) \left(L_{E,t} + \Psi \hat{L}_{H,t} \right).$$

Now, we can substitute out the spreads $R_{E,t} - R_t$ and $R_{H,t} - R_t$ using the definitions (84) and (85) that we have derived above:

$$E_{B,t}R_{B,t+1} = (L_{E,t} + \Psi\hat{L}_{H,t})\left(\tau_B\Phi(z_{B,t+1}) + \frac{\tau_B}{\sigma_B}\phi(z_{B,t+1})\frac{L_{E,t} + \Psi\hat{L}_{H,t}}{D_t + \Psi\hat{D}_t}\right) -$$
$$- \frac{\tau_B}{\sigma_B}\phi(z_{B,t+1})(L_{E,t} + \Psi\hat{L}_{H,t})\left(\frac{R_{E,t}L_{E,t}}{R_{E,t}L_{E,t} + \Psi\hat{L}_{H,t}R_{H,t}} + \frac{R_{H,t}\Psi\hat{L}_{H,t}}{R_{E,t}L_{E,t} + \Psi\hat{L}_{H,t}R_{H,t}}\right) + E_{B,t}R_t - \tau_B\Phi(z_{B,t+1})(L_{E,t} + \Psi\hat{L}_{H,t}).$$

After some simplifications, the result is the following:

$$E_tR_{B,t+1} = E_t\left(\frac{\tau_B}{\sigma_B}\phi(z_{B,t+1})\frac{L_{E,t} + \Psi\hat{L}_{H,t}}{D_t + \Psi\hat{D}_t} + R_t\right).$$

If we compare this expression with the first-order condition (81) for deposits, we can finally establish that μ_t, the shadow price of the balance-sheet constraint, is equal to the discounted future return on equity:

$$\mu_t = \beta\frac{\Lambda_{t+1}}{\Lambda_t}R_{B,t+1} \tag{86}$$

We can use this result to write the first-order condition for equity (80) as it is reported in Section 2:

$$1 + \frac{\xi_B}{2}\Omega_{B,t}^2 + \xi_B\Omega_{B,t} = \beta\frac{\Lambda_{t+1}}{\Lambda_t}R_{B,t+1}. \tag{87}$$

Appendix C Calibrated parameters

The next page contains the table with the values that we have specified for all the parameters. Please refer to Section 3.1 for the discussion.

Table 3
Calibrated parameters

Symbol	Name	Value
	Households	
Ψ	Impatient household population	0.2
$\hat{\beta}$	Discount factor, impatient households	0.984
β	Discount factor, patient households	0.995
ζ	Utility weight of deposits	0.14
ι	Demand elasticity of deposits	1.5
ψ_{SS}	Utility weight of housing	0.23
κ	Labor productivity of impatient households	1.2
	Production	
δ_H	Housing stock depreciation	0.005
δ_K	Capital stock depreciation	0.023
α_Y	Capital share, non-tradables	0.35
ν	Demand elasticity, non-tradables	11
α_X	Imports share in export production	0.6
α_Z	Capital share in export production	0.6
α_F	Imports share in final good production	0.55
ν_F	Elasticity of substitution, final-good prod.	2
	Banks and credit markets	
σ_B	Volatility of idiosyncratic bank shocks	0.025
δ_B	Divined payout to equity	0.03
τ_B	Penalty for insufficient bank capital	0.02
τ_{LTV}	Penalty for excessive LTV	0.02
τ_{DSTI}	Penalty for excessive DSTI	0.02
N	Mortgage duration used to compute DSTI	16
σ_H	Idiosyncratic volatility of housing	0.25
μ_H	Loss given mortgage default	0.1
σ_K	Idiosyncratic volatility of capital return	0.3
μ_K	Capital loss given entrepreneurial default	0.1
σ_W	Idiosyncratic volatility of wage	0.3
R^*	Eurozone interest rate	1.00125
B/GDP	Zero-premium debt-to-GDP ratio	0.6
η	Interest premium sensitivity	0.02
	Policies	
R	Central bank's policy rate	1.00224
g_B	Minimum capital requirement	0.1
g_{LTV}	Loan-to-value ratio cap	0.8
g_{DSTI}	Debt-service-to-income ratio cap	0.5
γ	Government spending share	0.16

In addition, we have set the consumption-habit parameter $\chi = 0.75$ in line with the literature; and bank equity adjustment cost parameter $\xi_B = 100$ to reflect the fact that banks cannot change equity quickly.

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