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**Doctoral Thesis**

## Financial frictions in a housing economy: Multiple credit constraints, internal migration, and bank runs

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**Ph.D. Thesis**

Marcus Mølbak Ingholt

Financial Frictions in a Housing Economy:  
Multiple Credit Constraints, Internal Migration, and  
Bank Runs

Supervisors: Emiliano Santoro and Søren Hove Ravn

Date of submission: March 28, 2019



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# Introduction in English

More than a decade has now passed since rapidly declining house prices triggered a global financial crisis that developed into a global recession, the speed and depth of which were unprecedented in recent history. The overarching objective of this Ph.D. thesis is to improve our understanding of how simple price adjustments in the housing market could cause havoc to the functioning of the global economy to such an extent.

At first sight, it may not be obvious that housing markets matter greatly for aggregate economic activity. For instance, residential investments constitute a small share – 4.4 pct. in the United States (U.S.) and 5.4 pct. in Denmark – of the gross domestic product.<sup>1</sup> However, real estate, in addition to providing housing services to families, serves as collateral on mortgage loans, home equity loans, and home equity lines of credit. A corollary of this servitude is that the supply of collateralized credit to homeowners expands and contracts roughly proportionally to the house price cycle. In consequence, house prices may act as impetuses that stimulate and depress economic activity ([Kiyotaki and Moore, 1997](#); [Iacoviello, 2005](#)). This collateral channel – in conjunction with other mechanisms linking house prices, credit, and real activity – constitute the theoretical foundation of the thesis. The thesis consists of three self-contained chapters, in addition to this introduction. All chapters focus on the U.S. economy, but have implications that reach well beyond this scope.

Homeowners realistically face *both* loan-to-value (LTV) and debt-service-to-income (DTI) constraints when they apply for mortgage loans. Despite this, the existing literature has mostly focused on the role of LTV constraints in causing financial acceleration. In the **first chapter** of the thesis ("Multiple Credit Constraints and Time-Varying Macroeconomic Dynamics"), I study the macroeconomic implications of homeowners simultaneously facing LTV and DTI constraints on the amount they may borrow. I build a macroeconomic model that features both constraints, entering in an occasionally binding fashion. In the model, households effectively face the single constraint that yields the lowest amount of debt at a given point in time. Through a nonlinear estimation of the model, I identify when each constraint was binding over the period 1975-2017. I discover that the LTV constraint often binds in contractions, when house prices are relatively low, while the DTI constraint mostly binds in expansions, when mortgage rates are relatively

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<sup>1</sup>These shares are calculated over the period 1966-2018. Sources: The U.S. Bureau of Economic Analysis and Statistics Denmark.

high. Further, I find that DTI standards were relaxed during the mid-2000s credit boom. In the light of this, the boom could have been avoided by tighter DTI limits. A lower LTV limit would contrarily not have prevented the boom, since soaring house prices rendered this constraint unlikely to bind. In this way, whether or not a constraint binds shapes its effectiveness as a macroprudential tool. Toward the end of the chapter, I provide evidence from county-level panel data that corroborates the role of multiple credit constraints for the emergence of nonlinear dynamics.

In the following two chapters of the thesis, I continue to model the impact of mortgage credit and LTV constraints. At the same time, I delve into a broader array of distortions than the ones generated solely by the collateral channel highlighted above.

In particular, in the **second chapter** ("Not Moving and Not Commuting: Macroeconomic Responses to a Housing Lock-In"), I study the effects of housing market turmoil on spatial labor mobility and wage setting. I start by documenting that internal, cross-county migration correlates positively with house prices and mortgage credit and negatively with wage inflation. I then explain these facts in a macroeconomic model featuring a relocation-contingent refinance requirement and a New Keynesian labor market (Erceg, Henderson, and Levin, 2000). In this framework, declining house prices and tight credit conditions cause homeowners to become technically insolvent, impeding their spatial mobility (Stein, 1995; Henley, 1998). This housing lock-in severely restrains cross-area competition between workers for jobs, causing wages and unemployment to rise. By estimating the model, I find that adverse housing market shocks were the prime culprits behind the historic decline in internal migration from 2005 to 2010. Absent this decline, the unemployment rate would have been 0.6 p.p. lower in the end of 2009.

Another repercussion of falling house prices is that this motivates homeowners to default on their collateralized debt if the market value of their home falls below their outstanding obligations. In the **third chapter** ("Mortgage Defaults, Bank Runs, and Regulation in a Housing Economy"), written with Johannes Poeschl and Xue Zhang, we study the implications of such mortgage default events. In our model, endogenous house price drops can lead to bank runs if losses on mortgage lending push the liquidation value of the banking sector below the value of the sector's outstanding deposits. Using only a technology shock, we show that the model explains historical movements in key variables, such as consumption, house prices, the mortgage default rate, and the probability of bank runs. We then employ the model to evaluate different macroprudential policies. Stricter loan-to-value standards and bank capital requirements reduce the frequency of bank panics, but at the cost of impeding financial intermediation over the business cycle. A dynamic capital requirement is contrarily able to both curb systemic risk and support intermediation, as this tightening only binds in times of financial distress.

While the thesis – along with much ongoing work by other researchers – brings us closer to understanding how asset price and credit fluctuations affect the economy, many questions remain unanswered. This becomes clear by reading the theoretical macrofinance

literature. This literature has recently produced a large number of convincing frameworks that, nonetheless, deliver strikingly different predictions, due to disparities in modeling assumptions. As examples of this, credit supply constraints ([Justiniano, Primiceri, and Tambalotti, 2018](#)), LTV constraints on firms ([Liu, Wang, and Zha, 2013](#)), earnings-based credit constraints on firms ([Drechsel, 2018](#)), long-term debt contracts ([Chatterjee and Eyigungor, 2012](#); [Kydland, Rupert, and Šustek, 2016](#)), and rental markets ([Kaplan, Mitman, and Violante, 2017](#)) are crucial assumptions in certain models and completely absent in most other models. The frictions stressed in this thesis – DTI constraints, mobility-contingent wage setting, and bank runs – also belong to this category. Some of these occasionally modeled frictions may not be mutually exclusive. Even so, further work is needed in order to understand which assumptions are appropriate for which research questions. Such work would be a crucial step toward a unification of the competing approaches.

There is also scope for further empirical research within macrofinance. A literature already exists on how different economic channels impact credit issuance and real activity. Such channels include variation in households' net worth ([Campbell and Cocco, 2007](#); [Mian and Sufi, 2011](#)), the credit supply to households ([Mondragon, 2018](#)), firms' real estate wealth ([Chaney, Sraer, and Thesmar, 2012](#)), and the credit supply to firms ([Chodorow-Reich, 2014](#)). However, this literature mainly considers the effects of these channels separately, despite the possibility of important interactions between them.<sup>2</sup> Thus, an exploration of how the different credit channels interact seems fruitful. For instance, increments in homeowners' net worth might only enable them to extract more equity if their banks' leverage constraints are sufficiently lax, as emphasized from a theoretical perspective in the third chapter. Moreover, in the presence of multiple borrowing constraints, the response of households and firms to changes in the determinants of credit should depend discretely on which constraint that binds, as shown theoretically in the first chapter.

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<sup>2</sup>Other researchers have recently begun exploring these issues. For instance, [Bhutta and Keys \(2016\)](#) and [Andersen and Leth-Petersen \(2019\)](#) interact house price and interest rate changes, and find that they amplify each other considerably.





# Introduction in Danish

Der er nu gået mere end et årti siden, at hastigt faldende boligpriser udløste en global finanskriser, som udviklede sig til en global recession, hvis hastighed og dybde var uden fortilfælde i nyere historie. Den overordnede målsætning med denne ph.d.-afhandling er at give en bedre forståelse for, hvordan simple prisjusteringer på boligmarkedet kunne ødelægge den globale økonomis funktionsmuligheder i sådan et omfang.

Det er ikke nødvendigvis indlysende, at boligmarkedet har en stor betydning for den samlede økonomiske aktivitet. For eksempel udgør boliginvesteringer kun en lille andel – 4,4 pct. i USA og 5,4 pct. i Danmark – af bruttonationalproduktet.<sup>3</sup> Udover at levere bolig tjenester til familier, tjener fast ejendom imidlertid også som kaution for realkreditlån, boliglån og boligkreditter. Den naturlige følge heraf er, at udbuddet af boliglån udvider og sammentrækker sig omtrent proportionalt med boligprisudviklingen. Boligpriser kan dermed fungere som en kraft, der stimulerer og svækker økonomisk aktivitet (Kiyotaki and Moore, 1997; Iacoviello, 2005). Denne kautionskanal – i forening med andre mekanismer, der forbinder boligpriser, gæld og realøkonomisk aktivitet – udgør det teoretiske grundlag for afhandlingen. Afhandlingen består, udover denne introduktion, af tre selvstændige kapitler. Alle kapitlerne fokuserer på USA's økonomi, men har implikationer, som rækker væsentligt længere end til denne afgrænsning.

Når boligejere ansøger om boliglån, mødes de i praksis *både* med krav om en maksimal belåningsgrad og med krav om et maksimalt forhold mellem deres gældsbyrde og indkomst. På trods af dette har den eksisterende litteratur hovedsageligt fokuseret på belåningsgradsbegrænsningernes rolle i at forårsage finansiel acceleration. I afhandlingens **første kapitel** ("Multiple Credit Constraints and Time-Varying Macroeconomic Dynamics") undersøger jeg de makroøkonomiske konsekvenser af, at der stilles krav både til boligejeres belåningsgrad og til forholdet mellem deres gældsbyrde og indkomst. Jeg bygger en makroøkonomisk model, hvori begge krav indgår som lejlighedsvist bindende begrænsninger. I modellen bliver husholdningerne effektivt mødt af den ene begrænsning, som på et givent tidspunkt giver den laveste gældsmængde. Gennem en ikke-lineær estimation af modellen identificerer jeg, hvornår hver begrænsning bandt i løbet af perioden 1975-2017. Jeg finder, at belåningsgradsbegrænsningen ofte binder i lavkonjunkturer, når boligpriserne er relativt lave, mens gældsbyrdesbegrænsningen for det meste binder i

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<sup>3</sup>Andelene er beregnet på tværs af perioden 1966-2018. Kilder: The U.S. Bureau of Economic Analysis og Danmarks Statistik.

højkonjunkturer, når realkreditrenterne er relativt høje. Ydermere finder jeg, at gældsudelseskravene blev lempet i løbet af kreditboomet i midt-2000'erne. Set i lyset af dette kunne boomet have været undgået ved hjælp af strammere gældsudelseskrav. Et lavere belåningsgradskrav ville modsat ikke have forhindret boomet, eftersom stærkt stigende boligpriser løsnede denne begrænsning. På den måde bliver lånebegrænsningernes effektivitet som makroprudentielle redskaber formet af, hvorvidt de binder eller ej. I slutningen af kapitlet dokumenterer jeg med paneldata på tværs af amter lånebegrænsningernes relevans i at frembringe ikkelineære dynamikker.

I afhandlingens efterfølgende to kapitler fortsætter jeg med at modellere betydningen af boliggæld og belåningsgradsbegrænsninger. Samtidigt dykker jeg ned i et bredere udsnit af forvridninger, end dem som alene opstår som følge af den kautionskanal, som blev fremhævet foroven.

I det **andet kapitel** ("Not Moving and Not Commuting: Macroeconomic Responses to a Housing Lock-In") undersøger jeg konsekvenserne for geografisk arbejdskraftsmobilitet og løndannelse af uro på boligmarkedet. Jeg starter med at dokumentere, at intern migration på tværs af amter korrelerer positivt med boligpriser og boliggæld og negativt med løninflation. Jeg forklarer dernæst disse forhold i en makroøkonomisk model, som indeholder et flyttebetinget refinansieringskrav og et nykeynesiansk arbejdsmarked (Erceg et al., 2000). Med dette modelapparat vil faldende boligpriser og strammere kreditkrav gøre boligejere teknisk insolente, og dermed bremse deres geografiske mobilitet (Stein, 1995; Henley, 1998). Denne fastlåsning i egen bolig begrænser alvorligt konkurrencen om jobs mellem arbejdere på tværs af områder, og bevirker, at lønningerne og arbejdsløsheden stiger. Ved at estimere modellen finder jeg, at ugunstige boligmarkedsstød var den primære årsag til det historiske fald i intern migration fra 2005 til 2010. Uden dette fald ville arbejdslededsraten have været 0,6 pct.-point lavere i slutningen af 2009.

En anden følge af faldende boligpriser er, at det motiverer boligejere til at misligholde deres boliggæld, hvis deres huses markedsværdi bliver mindre end deres gældsforpligtigelser. I det **tredje kapitel** ("Mortgage Defaults, Bank Runs, and Regulation in a Housing Economy"), skrevet sammen med Johannes Poeschl og Xue Zhang, undersøger vi konsekvenserne af sådanne misligholdelser af boliggælden. I vores model kan endogene boligprisfald føre til bankstormløb, hvis tab på boligudlån skubber banksektorens realiseringsværdi ned under værdien af indlånene i sektoren. Ved hjælp af teknologistød alene viser vi, at modellen forklarer historiske bevægelser i centrale variable, såsom forbrug, boligpriser, misligholdelsesraten og sandsynligheden for bankstormløb. Vi bruger dernæst modellen til at evaluere forskellige makroprudentielle politikker. Strengere belåningsgradskrav og kapitalkrav til banker reducerer hyppigheden af bankkriser, men med den omkostning, at den finansielle formidling begrænses på tværs af konjunkturerne. Et dynamisk kapitalkrav er modsat i stand til både at dæmme op for systemiske risici og understøtte finansiell formidling, eftersom denne begrænsning kun gælder i perioder med store finansielle usikkerheder.

På trods af, at afhandlingen – sammen med mange andre forskeres igangværende projekter – bringer os tættere på at forstå, hvordan udsving i aktivpriser og gæld påvirker økonomien, forbliver mange spørgsmål ubesvarede. Dette ses tydeligt i den teoretiske makrofinansieringslitteratur. Denne litteratur har i den seneste tid frembragt flere overbevisende modelapparater, som ikke desto mindre giver bemærkelsesværdigt afvigende konklusioner på grund af forskelle i modelantagelser. Som eksempler herpå er kreditudbudsbegrænsninger ([Justiniano et al., 2018](#)), belåningsgradsbegrænsninger på virksomheder ([Liu et al., 2013](#)), indtjeningsbaserede lånebegrænsninger på virksomheder ([Drechsel, 2018](#)), langsigtede gældskontrakter ([Chatterjee and Eyigungor, 2012](#); [Kydland et al., 2016](#)) og lejemarkeder ([Kaplan et al., 2017](#)) vigtige antagelser i nogle modeller og fuldstændigt fraværende i de fleste andre modeller. Friktionerne betonet i denne afhandling – gældsudbuds begrænsninger, mobilitetsbetinget løndannelse og bankstormløb – tilhører også denne kategori. Nogle af disse lejlighedsvist modellerede friktioner udelukker givetvist ikke hinanden. Ikke desto mindre er det nødvendigt med yderligere undersøgelser for at kunne fastslå hvilke antagelser, der er hensigtsmæssige for at svare på et givent forskningsspørgsmål. Et sådant arbejde vil være et afgørende skridt i retning af en forening af de konkurrerende tilgange.

Der er endvidere behov for mere empirisk forskning inden for makrofinansiering. Der eksisterer allerede en litteratur om, hvordan forskellige økonomiske kanaler påvirker kreditudstedelse og realøkonomisk aktivitet. Sådanne kanaler indbefatter variation i husholdningers nettoformue ([Campbell and Cocco, 2007](#); [Mian and Sufi, 2011](#)), kreditudbuddet til husholdninger ([Mondragon, 2018](#)), værdien af virksomheders faste ejendom ([Chaney et al., 2012](#)) og kreditudbuddet til virksomheder ([Chodorow-Reich, 2014](#)). Denne litteratur betragter imidlertid primært effekterne af disse kanaler separat på trods af muligheden for, at der findes vigtige interaktioner mellem dem.<sup>4</sup> En udforskning af, hvordan de forskellige kanaler interagerer, virker således tjenlig. Det er for eksempel muligt, at vækst i husejeres nettoformue kun tillader dem at låne mere, såfremt deres bankers udlånsbegrænsninger er tilstrækkeligt løse, som understreget fra et teoretisk perspektiv i det tredje kapitel. Ydermere bør husholdningers og virksomheders reaktion på ændringer i de ovennævnte faktorer under forekomst af multiple lånebegrænsninger afhænge diskret af hvilken begrænsning, der binder, som vist teoretisk i det første kapitel.

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<sup>4</sup>Andre forskere er fornyligt begyndt at udforske disse emner. For eksempel interagerer [Bhutta and Keys \(2016\)](#) og [Andersen and Leth-Petersen \(2019\)](#) ændringer i boligpriser og renter, og finder at de forstærker hinanden betragteligt.



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Copenhagen, March 2019







# Chapter 1

## Multiple Credit Constraints and Time-Varying Macroeconomic Dynamics

*By:* Marcus Mølbak Ingholt

I build a DSGE model where households face two occasionally binding credit constraints: a loan-to-value (LTV) constraint and a debt-service-to-income (DTI) constraint. From an estimation of the model, I infer when each constraint was binding over the 1975-2017 timespan. The LTV constraint often binds in contractions, when house prices are relatively low – and the DTI constraint mostly binds in expansions, when mortgage rates are relatively high. Moreover, both constraints unbind during robust expansions. I also infer that DTI standards were relaxed during the mid-2000s credit boom, going from a maximally allowed DTI ratio of 28 pct. in 1999 to 35 pct. in 2006. In the light of this, the boom could have been avoided by tighter DTI limits. A lower LTV limit would contrarily not have prevented the boom, since soaring house prices slackened this constraint. In this way, whether or not a constraint binds shapes its effectiveness as a macroprudential tool. The role of multiple credit constraints for the emergence of nonlinear dynamics is corroborated by county panel data.

*JEL classification:* C33, D58, E32, E44.

*Keywords:* Multiple credit constraints. Nonlinear estimation of DSGE models. State-dependent credit origination.

# 1 Introduction

Numerous empirical and theoretical papers emphasize the role of the loan-to-value (LTV) limits on loan applicants in causing financial acceleration.<sup>1</sup> In these contributions, the supply of collateralized credit to households moves up and down proportionally to asset prices, thereby acting as an impetus that expands and contracts the economy. In reality, however, banks *also* impose debt-service-to-income (DTI) limits on loan applicants.<sup>2</sup> Given that LTV and DTI constraints generally do not allow for the same amounts of debt, households effectively face the single constraint that yields the lowest amount. In turn, endogenous switching between the two constraints can occur depending on various determinants of mortgage borrowing, such as house prices, incomes, and mortgage rates. This then raises some questions, all of which are fundamental to macroeconomics and finance. When and why have LTV and DTI limits historically restricted mortgage borrowing? Did looser LTV or DTI limits cause the credit boom prior to the Great Recession, and could regulation have limited the resulting bust? How, if at all, does switching between different credit constraints affect the propagation and amplification of macroeconomic shocks? The answers to these questions have profound implications for how we model the economy and implement macroprudential policies. For instance, if house price growth does not lead to a significant credit expansion when households' incomes are below a certain threshold, models with a single credit constraint will either overestimate the role of house prices or underestimate the role of incomes in enhancing booms. Consequently, macroprudential policymakers will misidentify the risks associated with house price and income growth.

In order to understand these issues better, I develop a tractable New Keynesian dynamic stochastic general equilibrium (DSGE) model with two occasionally binding credit constraints: an LTV constraint and a DTI constraint. With this setup, homeowners must fulfill a collateral requirement and a debt service requirement in order to qualify for a mortgage loan. The LTV constraint is the solution to a debt enforcement problem, as in [Kiyotaki and Moore \(1997\)](#). The DTI constraint is a generalization of the natural borrowing limit in [Aiyagari \(1994\)](#). I estimate the model by Bayesian maximum likelihood on time series covering the U.S. economy over the 1975-2017 timespan. The solution of the model is based on a piecewise first-order perturbation method, so as to handle the occasionally binding nature of the constraints ([Guerrieri and Iacoviello, 2015, 2017](#)). Using this framework, I present three main sets of results.

The first set relates to the historical evolution in credit conditions. The estimation

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<sup>1</sup>See, e.g., [Kiyotaki and Moore \(1997\)](#), [Iacoviello \(2005\)](#), [Iacoviello and Neri \(2010\)](#), [Mendoza \(2010\)](#), [Jermann and Quadrini \(2012\)](#), [Liu et al. \(2013\)](#), [Liu, Miao, and Zha \(2016\)](#), [Justiniano, Primiceri, and Tambalotti \(2015\)](#), [Guerrieri and Iacoviello \(2017\)](#), [Jensen, Petrella, Ravn, and Santoro \(2017\)](#), and [Jensen, Ravn, and Santoro \(2018\)](#).

<sup>2</sup>Appendix A reports the DTI limits that the ten largest U.S. retail banks specify on their websites. All mortgage issuing banks set front-end limits of 28 pct. or back-end limits of 36 pct. [Greenwald \(2018\)](#) shows that borrowers bunch around institutional DTI limits, in addition to institutional LTV limits. [Johnson and Li \(2010\)](#) aptly find that households with high DTI ratios are far more likely to be turned down for credit than comparable households with low ratios.

allows me to identify when the two credit constraints were binding and which shocks caused them to bind. At least one constraint binds throughout most of the period, signifying that borrowers have generally been credit constrained. The LTV constraint often binds during and after recessions, when house prices, which largely determine housing wealth, are relatively low (e.g., 1975-1979, 1990-1998, and 2009-2017). The DTI constraint reversely mostly binds in expansions, when mortgage rates, which impact debt services, are relatively high, due to countercyclical monetary policy (e.g., 1980-1985, 1999-2002, and 2005-2008). Both constraints unbind during powerful expansions if both house prices and incomes rise sufficiently (e.g., 2003-2004).<sup>3</sup> In this way, like [Guerrieri and Iacoviello \(2017\)](#), I establish that the LTV constraint was slack in 1999-2007. However, in contrast to their findings, I also conclude that this did not imply that homeowners could borrow freely, because of DTI requirements.

[Corbae and Quintin \(2015\)](#) and [Greenwald \(2018\)](#) hypothesize a relaxation of DTI limits as the cause of the mid-2000s credit boom. My estimation corroborates this hypothesis, inferring that the maximally allowed debt service to income ratio was raised from 28 pct. in 1999 to 35 pct. in 2006. To my knowledge, this is the first evidence of a DTI relaxation obtained within an estimated model. Such a relaxation is consistent with [Justiniano, Primiceri, and Tambalotti \(2017, 2018\)](#), who find that looser LTV limits cannot explain the credit boom, and that the fraction of borrowers presenting full income documentation dropped substantially in 2000-2007. [Justiniano et al. \(2018\)](#) also argue that it was an increase in credit supply which caused the surge in mortgage debt. My results qualify these previous discoveries, together suggesting that the increase in credit supply translated into a relaxation of DTI limits. The results also show that credit standards were eased during the financial deregulation in the early-1980s and tightened following the Stock Market Crash of 1987, the Savings and Loan Crisis of the late-1980s, and the Great Recession, in line with narrative accounts ([Campbell and Hercowitz, 2009](#); [Mian, Sufi, and Verner, 2017](#)) and VAR estimates ([Prieto, Eickmeier, and Marcellino, 2016](#)).

The second set of results relates to the optimal timing and implementation of macroprudential policy. Recent studies show that credit expansions predict subsequent banking and housing market crises (e.g., [Mian and Sufi, 2009](#); [Schularick and Taylor, 2012](#); [Baron and Xiong, 2017](#)). Motivated by this, I consider how mortgage credit would historically have evolved if LTV and DTI limits had responded countercyclically to deviations of credit from its long-run trend. I find that countercyclical DTI limits are effective at curbing increases in mortgage debt, since these increases typically occur in expansions, when the DTI constraint is binding. For instance, mortgage credit growth is halved during the mid-2000s boom in my policy simulation. The flip-side of this result is that countercyclical LTV limits cannot prevent mortgage debt from rising, since this constraint typically is slack in expansions. Tighter LTV limits would therefore not have been able to prevent the

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<sup>3</sup>Whether or not both constraints unbind following a given housing wealth and income appreciation depends on the patience of borrowers. Since this parameter is estimated, the model allows, but does not *a priori* impose, that both credit constraints should unbind during powerful expansions.

mid-2000s credit boom. Countercyclical LTV limits can, however, abate the adverse consequences of house price slumps on credit availability by raising credit limits. In this way, the lowest volatility in borrowing is reached by combining the LTV and DTI policies into a two-stringed policy entailing that *both* credit limits respond countercyclically. Macroprudential policy then takes into account that the effective policy tool changes over the business cycle, with an LTV tool in contractions and a DTI tool in expansions. Because this policy limits the deleveraging-induced flow of funds from borrowers to lenders in recessionary episodes, the policy efficiently redistributes consumption risk from borrowers to lenders. Thus, congruous with common definitions of value-at-risk, consumption-at-risk is lower for borrowers and higher for lenders under the two-stringed policy. Such theoretical guidance on how to combine multiple credit constraints for macroprudential purposes is scarce within the existing literature, as also noted by [Jácome and Mitra \(2015\)](#).<sup>4</sup>

The third set of results relates to how endogenous switching between credit constraints transmits shocks nonlinearly through the economy. Housing preference and credit shocks exert asymmetric effects on real activity, in that adverse shocks have larger effects than similarly sized favorable shocks. Adverse shocks are amplified by borrowers lowering their housing demand, which tightens the LTV constraint and forces borrowers to delever further. Favorable shocks are, by contrast, dampened by countercyclical monetary policy, which raises the mortgage rate and, *ceteris paribus*, tightens the DTI constraint. Housing preference and credit shocks also exert state-dependent effects, since these shocks have larger effects in contractions than in expansions. Thus, shocks that occur when the LTV constraint binds (typically in contractions) are amplified by housing demand moving in the same direction as the shock, while shocks that occur when the DTI constraint binds (typically in expansions) are curbed by countercyclical monetary policy. These predictions of nonlinear responses fit with an emerging body of empirical studies.<sup>5</sup> Models with only an occasionally binding LTV constraint, in comparison, have difficulties in producing nonlinear dynamics. State-of-the-art models, such as [Guerrieri and Iacoviello \(2017\)](#) or [Jensen et al. \(2018\)](#), do capture some nonlinearity following *large favorable* shocks that unbind this constraint. However, the reactions of these models are linear up until the point where the LTV constraint unbinds.<sup>6</sup>

As a final contribution, I use a county-level panel dataset to test two key predictions of homeowners facing both an LTV constraint and a DTI constraint. The predictions are that (i) house price growth shall not allow homeowners to borrow more if incomes are sufficiently low, and (ii) income growth shall not allow homeowners to borrow more if house prices are sufficiently low. My identification strategy is based on Bartik-type house price and income instruments, along with county and state-year fixed effects. The specific

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<sup>4</sup>An exception to this is [Greenwald \(2018\)](#), who focuses on policy around the Great Recession.

<sup>5</sup>See, e.g., [Engelhardt \(1996\)](#), [Skinner \(1996\)](#), [Davig and Hakkio \(2010\)](#), [Hubrich and Tetlow \(2015\)](#), [Kuttner and Shim \(2016\)](#), [Prieto et al. \(2016\)](#), and [Barnichon, Matthes, and Ziegenbein \(2017\)](#).

<sup>6</sup>I verify this point by also building and estimating a model that only has an occasionally binding LTV constraint. The marginal data density massively favors the baseline model over the LTV model.

test involves estimating the elasticities of mortgage loan origination with respect to house prices and personal incomes, importantly after partitioning the elasticities based on the detrended house price and income levels. The exercise confirms that both elasticities are highly state-dependent. The elasticity with respect to house prices is zero when incomes are below their long-run trend and 0.69 when they are above. Correspondingly, the elasticity with respect to incomes is zero when house prices are below their long-run trend and 0.43 when they are above. Thus, the exercise certifies that house price (income) growth does not increase credit origination when households' incomes (house prices) are low, in keeping with a simultaneous imposition of LTV and DTI constraints. These estimates are among the first, in an otherwise large micro-data literature, to suggest that house prices and incomes amplify each others' effect on credit origination.

The rest of the chapter is structured as follows. Section 2 discusses how the chapter relates to the existing literature. Section 3 presents the theoretical model. Section 4 performs the Bayesian estimation of the model. Section 5 highlights the nonlinear dynamics that the credit constraints introduce. Section 6 decomposes the historical evolution in credit conditions. Section 7 conducts the macroprudential policy experiment. Section 8 presents the panel evidence on state-dependent mortgage debt elasticities. Section 9 contains the concluding remarks.

## 2 Related Literature

The chapter is, to my knowledge, the first to include both an occasionally binding LTV constraint and an occasionally binding DTI constraint in the same estimated general equilibrium model. A small theoretical literature already studies house price propagation through occasionally binding LTV constraints. [Guerrieri and Iacoviello \(2017\)](#) demonstrate that the macroeconomic sensitivity to house price changes is smaller during booms (when LTV constraints may unbind) than during busts (when LTV constraints bind). [Jensen et al. \(2018\)](#) study how relaxations of LTV limits lead to an increased macroeconomic volatility, up until a point where the limits become sufficiently lax and credit constraints generally unbind, after which this pattern reverts. [Jensen et al. \(2017\)](#) document that the U.S. business cycle has increasingly become negatively skewed, and explain this through secularly increasing LTV limits that dampen the effects of expansionary shocks and amplify the effects of contractionary shocks.

A growing empirical literature documents the presence of substantial asymmetric and state-dependent responses to house price and financial shocks. [Barnichon et al. \(2017\)](#) show that increments in the excess bond premium have large and persistent negative real effects, while reductions have no significant effects, using a nonlinear vector moving average model and U.S., U.K., and Euro area data. They also show that increments have larger and more persistent effects on real activity in contractions than in expansions. In a similar manner, [Prieto et al. \(2016\)](#) show that house price and credit spread shocks have

larger impacts on GDP growth in crisis periods than in non-crisis periods, using a time-varying parameter VAR model and U.S. data. Finally, [Engelhardt \(1996\)](#) and [Skinner \(1996\)](#) show that consumption falls significantly following decreases in housing wealth, but does not rise following increases in housing wealth, using U.S. panel surveys. The existing piecewise linear models with LTV constraints cannot easily reproduce the non-linear effects of house price and financial shocks. Within these frameworks, nonlinearities only arise if the LTV constraint unbinds, which presupposes that debt quantity limits expand to the extent that borrowing demand becomes saturated. For instance, [Guerrieri and Iacoviello \(2017\)](#) need to apply a 20 pct. house price increase in order for their LTV constraint to unbind. Such kinds of expansionary events occur more rarely than simple switching between an LTV constraint and a DTI constraint in yielding the lowest debt quantity. Thus, while the LTV constraint does provide some business cycle nonlinearity in expansions, the nonlinearities of the two constraint model apply to a much broader set of scenarios.

[Greenwald \(2018\)](#) complementarily studies the implications of LTV and DTI constraints for monetary policy and the mid-2000s boom.<sup>7</sup> He relies on a calibrated model with an always binding credit constraint which is an endogenously weighted average of an LTV and a DTI constraint, and considers linearized impulse responses. The present chapter provides new insights into the implications of such multiple constraints. First, the estimation allows for a full-information identification of when the respective constraints were dominating over the long 1975-2017 timespan and the impact of stabilization policies.<sup>8</sup> Second, the discrete switching between the constraints generates asymmetric and state-dependent impulse responses, incompatible with linear models. Third, the occasionally binding constraints imply that borrowers may become credit unconstrained if both constraints unbind simultaneously, unlike in the case with always binding constraints.

The chapter is finally, again to my knowledge, the first to examine the interacting effects of house price and income growth on equity extraction, using cross-sectional or panel data. A large literature already studies the effects of house price growth on equity extraction and real activity.<sup>9</sup> However, this literature mainly considers the effects of separate variation in house prices, rather than the interacted effects of changes in house prices

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<sup>7</sup>The heterogeneous agents models in [Chen, Michaux, and Roussanov \(2013\)](#), [Gorea and Midrigan \(2017\)](#), and [Kaplan et al. \(2017\)](#) also impose both LTV and DTI constraints, but do not study their interactions over the business cycle. Moreover, while including rich descriptions of financial markets and risk, the models lack general equilibrium dynamics related to interactions between the constraints and housing demand and labor supply, output, and monetary and macroprudential policy. Focusing on firms' borrowing, [Drechsel \(2018\)](#) establishes a connection between corporations' current earnings and their access to debt, and formalizes this link through an earnings-based constraint.

<sup>8</sup>Formal identification is important, in that the relative dominance of the two constraints hinges on the magnitude and persistence of house price shocks relative to the magnitude and persistence of income and mortgage rate shocks. These moments, in turn, largely depend on the shock processes, which are difficult to calibrate accurately due to their reduced-form nature and cross-model inconsistency.

<sup>9</sup>See, e.g., [Engelhardt \(1996\)](#), [Skinner \(1996\)](#), [Campbell and Cocco \(2007\)](#), [Mian and Sufi \(2011\)](#), [Mian, Rao, and Sufi \(2013\)](#), [Bhutta and Keys \(2016\)](#), [Guerrieri and Iacoviello \(2017\)](#), [Cloyne, Huber, Ilzetzki, and Kleven \(2017\)](#), and [Guren, McKay, Nakamura, and Steinsson \(2018\)](#).

and other drivers of credit. A notable exception to this is [Bhutta and Keys \(2016\)](#), who interact house price and interest rate changes, and find that they amplify each other considerably. This prediction fits with my theoretical model, as simultaneous expansionary shocks to house prices and monetary policy there relax both credit constraints directly.

### 3 Model

The model has an infinite time horizon. Time is discrete, and indexed by  $t$ . The economy is populated by two representative households: a patient household and an impatient household. Households consume goods and housing services, and supply labor. Goods are produced by a representative intermediate firm, by combining employment and nonresidential capital. Retail firms unilaterally set prices subject to downward-sloping demand curves. The time preference heterogeneity implies that the patient household lends funds to the impatient household. The patient household also owns and operates the firms and nonresidential capital. The housing stock is fixed, but housing reallocations take place between households. The equilibrium conditions are derived in Appendices [B-C](#).

#### 3.1 Patient and Impatient Households

Variables and parameters without (with) a prime refer to the patient (impatient) household. The household types differ with respect to their pure time discount factors,  $\beta \in (0, 1)$  and  $\beta' \in (0, 1)$ , since  $\beta > \beta'$ . The economic size of each household is measured by its wage share:  $\alpha \in (0, 1)$  for the patient household and  $1 - \alpha$  for the impatient household.

The patient and impatient households maximize their utility functions,

$$\mathbb{E}_0 \left\{ \sum_{t=0}^{\infty} \beta^t s_{I,t} \left[ \chi_C \log(c_t - \eta_C c_{t-1}) + \omega_H s_{H,t} \chi_H \log(h_t - \eta_H h_{t-1}) - \frac{s_{L,t}}{1 + \varphi} l_t^{1+\varphi} \right] \right\}, \quad (1)$$

$$\mathbb{E}_0 \left\{ \sum_{t=0}^{\infty} \beta'^t s'_{I,t} \left[ \chi'_C \log(c'_t - \eta_C c'_{t-1}) + \omega_H s_{H,t} \chi'_H \log(h'_t - \eta_H h'_{t-1}) - \frac{s_{L,t}}{1 + \varphi} l_t^{1+\varphi} \right] \right\}, \quad (2)$$

where  $\chi_C \equiv \frac{1-\eta_C}{1-\beta\eta_C}$ ,  $\chi'_C \equiv \frac{1-\eta_C}{1-\beta'\eta_C}$ ,  $\chi_H \equiv \frac{1-\eta_H}{1-\beta\eta_H}$ ,  $\chi'_H \equiv \frac{1-\eta_H}{1-\beta'\eta_H}$ ,<sup>10</sup>  $c_t$  and  $c'_t$  denote goods consumption,  $h_t$  and  $h'_t$  denote housing,  $l_t$  and  $l'_t$  denote labor supply and, equivalently, employment measured in hours,  $s_{I,t}$  is an intertemporal preference shock,  $s_{H,t}$  is a housing preference shock, and  $s_{L,t}$  is a labor preference shock. Moreover,  $\eta_C \in (0, 1)$  and  $\eta_H \in (0, 1)$  measure habit formation in goods and housing consumption, while  $\omega_H \in \mathbb{R}_+$  weights the utility of housing services relative to the utility of goods consumption.<sup>11</sup>

<sup>10</sup>The scaling factors ensure that the marginal utilities of goods consumption and housing services are  $\frac{1}{c}$ ,  $\frac{1}{c'}$ ,  $\frac{\omega_H}{h}$ , and  $\frac{\omega_H}{h'}$  in the steady state.

<sup>11</sup>It is not necessary to weight the disutility of labor supply, since its steady-state level only affects the scale of the economy, as in [Justiniano et al. \(2015\)](#) and [Guerrieri and Iacoviello \(2017\)](#).



Utility maximization of the patient household is subject to the budget constraint,

$$\begin{aligned} c_t + q_t(h_t - h_{t-1}) + \frac{1 + r_{t-1}}{1 + \pi_t} b_{t-1} + k_t + \frac{\iota}{2} \left( \frac{k_t}{k_{t-1}} - 1 \right)^2 k_{t-1} \\ = w_t l_t + div_t + b_t + (r_{K,t} + 1 - \delta_K) k_{t-1}, \end{aligned} \quad (3)$$

where  $q_t$  denotes the real house price,  $r_t$  denotes the nominal net interest rate,  $\pi_t$  denotes net price inflation,  $b_t$  denotes net borrowing,  $k_t$  denotes nonresidential capital,  $w_t$  denotes the real wage,  $div_t$  denotes dividends from retail firms, and  $r_{K,t}$  denotes the real net rental rate of nonresidential capital.  $\iota \in \mathbb{R}_+$  measures capital adjustment costs, and  $\delta_K \in [0, 1]$  measures the depreciation of nonresidential capital.

Utility maximization of the impatient household is subject to the budget constraint,

$$c'_t + q_t(h'_t - h'_{t-1}) + \frac{1 + r_{t-1}}{1 + \pi_t} b'_{t-1} = w'_t l'_t + b'_t, \quad (4)$$

where  $b'_t$  denotes net borrowing, and  $w'_t$  denotes the real wage. Utility maximization of the impatient household is also subject to two occasionally binding credit constraints,

$$b'_t \leq (1 - \rho) \frac{b'_{t-1}}{1 + \pi_t} + \rho \xi_{LTV} s_{C,t} \mathbb{E}_t \{ (1 + \pi_{t+1}) q_{t+1} h'_t \}, \quad (5)$$

$$b'_t \leq (1 - \rho) \frac{b'_{t-1}}{1 + \pi_t} + \rho \xi_{DTI} s_{C,t} \mathbb{E}_t \left\{ \frac{(1 + \pi_{t+1}) w'_{t+1} l'_t}{\sigma + r_t} \right\}, \quad (6)$$

where  $s_{C,t}$  is a credit shock which shifts the credit limits imposed by both constraints. Thus, following [Kaplan et al. \(2017\)](#), shocks to the two credit limits are perfectly correlated, implying that the shocks do not, on impact, influence which constraint that binds.<sup>12</sup>  $\rho \in [0, 1]$  measures the share of homeowners who refinance in a given period. This specification allows a share of homeowners,  $(1 - \rho)$ , to roll over their existing mortgages without refinancing, as in [Guerrieri and Iacoviello \(2017\)](#).  $\xi_{LTV} \in [0, 1]$  measures the steady-state LTV limit,  $\xi_{DTI} \in [0, 1]$  measures the steady-state DTI limit, and  $\sigma$  measures the amortization rate on outstanding debt. The constraints require that homeowners fulfill the following collateral and debt service requirements on newly issued mortgage loans:

$$\tilde{b}'_t \leq \rho \xi_{LTV} s_{C,t} \mathbb{E}_t \{ (1 + \pi_{t+1}) q_{t+1} h'_t \} \quad \text{and} \quad (\sigma + r_t) \tilde{b}'_t \leq \rho \xi_{DTI} s_{C,t} \mathbb{E}_t \{ (1 + \pi_{t+1}) w'_{t+1} l'_t \},$$

where  $\tilde{b}'_t$  denotes newly issued net borrowing. A similar LTV constraint can be derived as the solution to a debt enforcement problem, as shown by [Kiyotaki and Moore \(1997\)](#). Appendix D shows that the DTI constraint can be derived separately as an incentive compatibility constraint on the impatient household, and that it is a generalization of the natural borrowing limit in [Aiyagari \(1994\)](#). Finally, the assumption  $\beta > \beta'$  implies that

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<sup>12</sup>Estimating uncorrelated credit shocks is unfeasible, because it is only the shocks to the constraint yielding the lowest debt quantity that are identified in the model estimation.

(5) or (6) always hold with equality in (but not necessarily around) the steady state.<sup>13</sup>

## 3.2 Firms

### Intermediate Firm

The intermediate firm produces intermediate goods, by hiring labor from both households and renting capital from the patient household. The firm operates under perfect competition. The profits to be maximized are given by

$$\frac{Y_t}{M_{P,t}} - w_t l_t - w'_t l'_t - r_{K,t} k_{t-1}, \quad (7)$$

subject to the available goods production technology,

$$Y_t = k_{t-1}^\mu (s_{Y,t} l_t^\alpha l'_t)^{1-\mu}, \quad (8)$$

where  $Y_t$  denotes goods production,  $M_{P,t}$  denotes an average gross price markup over marginal costs set by the retail firms, and  $s_{Y,t}$  is a labor-augmenting technology shock. Lastly,  $\mu \in (0, 1)$  measures the goods production elasticity with respect to nonresidential capital.

### Retail Firms

Retail firms are distributed over a unit continuum by product specialization. They purchase and assemble intermediate goods into retail firm-specific final goods at no additional cost. The final goods are then sold for consumption and nonresidential investment purposes. The specialization allows the firms to operate under monopolistic competition. All dividends are paid out to the patient household:

$$div_t \equiv \left(1 - \frac{1}{M_{P,t}}\right) Y_t. \quad (9)$$

The solution of the retail firms' price setting problem yields a New Keynesian Price Phillips Curve:

$$\pi_t = \beta \mathbb{E}_t \{\pi_{t+1}\} - \lambda_P \left( \log M_{P,t} - \log \frac{\epsilon_P}{\epsilon_P - 1} \right), \quad (10)$$

where  $\lambda_P \equiv \frac{(1-\theta_P)(1-\beta\theta_P)}{\theta_P}$ . Furthermore,  $\epsilon_P > 1$  measures the price elasticity of retail firm-specific goods demand, and  $\theta_P \in (0, 1)$  measures the Calvo probability of a firm not being able to adjust its price in a given period.

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<sup>13</sup>The results in Sections 6-7 are robust to letting the employment of impatient workers drive the aggregate variation in hours worked, leaving the employment of patient workers constant at its steady-state level.

### 3.3 Monetary Policy

The central bank sets the nominal net interest rate according to a Taylor-type monetary policy rule,

$$r_t = \tau_R r_{t-1} + (1 - \tau_R)r + (1 - \tau_R)\tau_P \pi_{P,t} + \varepsilon_{M,t}, \quad (11)$$

where  $r$  denotes the steady-state nominal net interest rate, and  $\varepsilon_{M,t}$  is a monetary policy innovation. Moreover,  $\tau_R \in (0, 1)$  measures deterministic interest rate smoothing, and  $\tau_P > 1$  measures the policy response to price inflation.<sup>14</sup>

### 3.4 Equilibrium

The model contains a goods market, a housing market, and a loan market, in addition to two redundant labor markets. The market clearing conditions are

$$c_t + c'_t + k_t - (1 - \delta_K)k_{t-1} + \frac{\iota}{2} \left[ \frac{k_t}{k_{t-1}} - 1 \right]^2 k_{t-1} = Y_t, \quad (12)$$

$$h_t + h'_t = \mathcal{H}, \quad (13)$$

$$b_t = -b'_t, \quad (14)$$

where  $\mathcal{H} \in \mathbb{R}_+$  measures the fixed aggregate stock of housing.

### 3.5 Stochastic Processes

All stochastic shocks except the monetary policy innovation follow AR(1) processes. The monetary policy innovation is a single-period innovation, so that any persistence in this policy is captured by interest rate smoothing, as in [Christiano, Motto, and Rostagno \(2014\)](#). All six stochastic innovations are normally independent and identically distributed, with a constant standard deviation.

## 4 Solution and Estimation of the Model

### 4.1 Methods

I solve the model with the perturbation method from [Guerrieri and Iacoviello \(2015, 2017\)](#). This allows me to account for the two occasionally binding credit constraints and handle the associated nonlinear solution when implementing the Bayesian maximum likelihood

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<sup>14</sup>I do not model a zero lower bound on the nominal interest rate, since my interest rate measure is the 30-year fixed rate mortgage average, which did not reach zero following the Great Recession. The federal funds rate realistically exercises a large influence on the 30-year mortgage rate through the yield curve. For instance, the correlation between the two rates was 94 pct., on average across 1975-2017. The results in Sections 6-7 are robust to measuring the interest rate by the effective federal funds rate.

estimation. The model economy will always be in one of four regimes, depending on whether the LTV constraint binds or not and whether the DTI constraint binds or not. The solution method performs a first-order approximation of each of the four regimes around the steady state of a reference regime (one of the four regimes). In the regime where both constraints are binding, the borrowing limits imposed by the two constraints are, as a knife-edge case, identical.<sup>15</sup> Outside this regime, the borrowing limits may naturally differ, causing discrete switching between which of the three other regimes that applies. As a reference regime, I choose the regime where both constraints are binding, in order to treat the constraints symmetrically.<sup>16</sup> The calibrations of  $\xi_{LTV}$  and  $\xi_{DTI}$  must consequently ensure that the right-hand sides of (5) and (6) are identical in the steady state. However, this restriction on the parameterization of the model does not entail that it is not possible to calibrate the model realistically. Instead, as will be evident in Subsection 4.3, a highly probable calibration can be reached. Once a constraint unbinds, the households will expect it to bind again at some forecast horizon.<sup>17</sup> The households therefore base their decisions on the expected duration of the current regime, which, in turn, depends on the state vector. As a result, the solution of the model is nonlinear in two dimensions. First, it is nonlinear *between* regimes, depending on which regime that applies. Second, it is nonlinear *within* each regime, depending on the expected duration of the regime.

When estimating the model, one cannot use the Kalman filter to retrieve the estimates of the innovations. This is because the policy functions depend nonlinearly on which constraint that binds, which, in turn, depends on the innovations. Instead, I recursively solve for the innovations, given the state of the economy and the observations, as in [Fair and Taylor \(1983\)](#).

Borrowing is an observed variable in the estimation. It is mainly the credit shock which ensures that the theoretical borrowing variable matches its empirical measure. When a credit constraint is binding, the credit shock has an immediate effect on borrowing through the binding constraint, leading to a direct econometric identification of the shock. When both constraints are slack, this direct channel is switched off, since the credit constraints no-longer contemporaneously predict borrowing. Despite this, the model will not suffer from stochastic singularity (i.e., fewer shocks than observed variables), since the credit shock also has an effect on borrowing when both constraints are slack. This effect, only now, works through the first-order condition of the impatient household with respect to

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<sup>15</sup>This complication is not present in [Guerrieri and Iacoviello \(2017\)](#), since their two constraints (an LTV constraint and a zero lower bound) restrict two variables (borrowing and the nominal interest rate).

<sup>16</sup>I avoid specifying a reference regime where only one constraint binds, since this could bias the model towards that regime. The regime where both constraints are slack is unfeasible as a reference regime, in that the time preference heterogeneity is inconsistent with both households being credit unconstrained in the steady state.

<sup>17</sup>The expectation that both credit constraints eventually will bind results from an expectation that the economy eventually returns to its reference regime, where both constraints are binding.

net borrowing:

$$\begin{aligned} u'_{c,t} + \beta'(1 - \rho)\mathbb{E}_t \left\{ s_{I,t+1} \frac{\lambda_{LTV,t+1} + \lambda_{DTI,t+1}}{1 + \pi_{t+1}} \right\} \\ = \beta' \mathbb{E}_t \left\{ u'_{c,t+1} \frac{1 + r_t}{1 + \pi_{t+1}} \right\} + s_{I,t}(\lambda_{LTV,t} + \lambda_{DTI,t}). \end{aligned}$$

Through recursive substitution  $v$  periods ahead, this condition can be restated as

$$\begin{aligned} u'_{c,t} = & \beta'^v \mathbb{E}_t \left\{ u'_{c,t+v} \prod_{j=0}^{v-1} \frac{1 + r_{t+j}}{1 + \pi_{t+j+1}} \right\} \\ & + \sum_{i=1}^{v-1} \beta'^i \mathbb{E}_t \left\{ s_{I,t+i} (\lambda_{LTV,t+i} + \lambda_{DTI,t+i}) \prod_{j=0}^{i-1} \frac{1 + r_{t+j}}{1 + \pi_{t+j+1}} \right\} \\ & - \sum_{i=1}^{v-1} \beta'^{i+1} (1 - \rho) \mathbb{E}_t \left\{ s_{I,t+i+1} \frac{\lambda_{LTV,t+i+1} + \lambda_{DTI,t+i+1}}{1 + \pi_{t+i+1}} \prod_{j=0}^{i-1} \frac{1 + r_{t+j}}{1 + \pi_{t+j+1}} \right\} \\ & + s_{I,t}(\lambda_{LTV,t} + \lambda_{DTI,t}) - \beta'(1 - \rho) \mathbb{E}_t \left\{ s_{I,t+1} \frac{\lambda_{LTV,t+1} + \lambda_{DTI,t+1}}{1 + \pi_{t+1}} \right\}, \end{aligned}$$

for  $v \in \{v \in \mathbb{Z} | v > 1\}$ . According to the expression, the current levels of consumption and (via the budget constraint) borrowing are pinned down by the current and expected future Lagrange multipliers for  $v \rightarrow \infty$ . The current multipliers are zero ( $\lambda_{LTV,t} = \lambda_{DTI,t} = 0$ ) when both constraints are slack. The expected future multipliers will, however, be positive at some forecast horizon, due to the model being stable with zero mean stochastic innovations. The current credit shock can thereby (along with any other shock) – through its persistent effects on future credit limits – have an effect on the expected future Lagrange multipliers and ultimately consumption and borrowing in the current period. As a result, when both constraint are slack, the credit shock is identified via the constraint that allows for the lowest amount of borrowing, hence is the closest to binding.

## 4.2 Data

The estimation sample covers the U.S. economy in 1975Q1-2017Q4, at a quarterly frequency.<sup>18</sup> The sample contains the following six time series: 1. Real personal consumption expenditures per capita. 2. Real home mortgage loan liabilities per capita. 3. Real house prices. 4. Real disposable personal income per capita. 5. Aggregate weekly hours per capita. 6. Quartered 30-year fixed rate mortgage average.

Series 1-5 are normalized relative to 1975Q1 and then log-transformed. They are lastly detrended by a one-sided HP filter (with a smoothing parameter of 100,000) in order to remove their low-frequency components, following [Guerrieri and Iacoviello \(2017\)](#). This fil-

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<sup>18</sup>The results in Sections 6-7 are robust to estimating the model on a sample covering the period 1985Q1-2017Q4 (i.e., starting after the Great Moderation).

**Table 1:** CALIBRATED PARAMETERS

Description		Value	Source or Steady-State Target
Time discount factor, pt. hh.	$\beta$	0.99	Annual net real interest rate: 4 pct.
Housing utility weight	$\omega_H$	0.31	Steady-state target <sup>a</sup>
Steady-state LTV limit	$\xi_{LTV}$	0.769	See text
Steady-state DTI limit	$\xi_{DTI}$	0.364	See text
Amortization rate	$\sigma$	1/104.2	Average original loan term <sup>b</sup>
Depreciation rate, non-res. cap.	$\delta_K$	0.025	Standard value
Capital income share	$\mu$	0.33	Standard value
Price elasticity of goods demand	$\epsilon$	5.00	Standard value
Calvo price rigidity parameter	$\theta$	0.80	<a href="#">Galí and Gertler (1999)</a> , <a href="#">Sbordone (2002)</a>
Stock of housing (log. value)	$\mathcal{H}$	1.00	Normalization

<sup>a</sup>The model is calibrated to match the average ratio of owner-occupied residential fixed assets to durable goods consumption expenditures (37.8) over the sample period.

<sup>b</sup>The model is calibrated to match the average loan term (104.2 quarters) on originated loans weighted by the original loan balance during 2000-2016 in Fannie Mae's Single Family Loan Acquisition Data.

ter produces plausible trend and gap estimates for the variables. For instance, the troughs of consumption and mortgage debt following the Great Recession lie 7 pct. and 23 pct. below the trend, in 2009Q3 and 2012Q4, according to the filter. Furthermore, the one-sided filter preserves the temporal ordering of the data, as the correlation of current observations with subsequent observations is not affected by the filter ([Stock and Watson, 1999](#)). Series 6 is demeaned. Data sources and time series plots are reported in Appendix [E](#).

### 4.3 Calibration and Prior Distribution

A subset of the parameters are calibrated using information complementary to the estimation sample. Table [1](#) reports the calibrated parameters and information on their calibration. I set the steady-state DTI limit ( $\xi_{DTI} = 0.36$ ), so that debt servicing relative to labor incomes *before taxes* may not exceed 28 pct., as in [Greenwald \(2018\)](#).<sup>19</sup> This value is identical to the typical front-end (i.e., excluding other recurring debts) DTI limit set by mortgage issuing banks in the U.S., according to Appendix [A](#). The number is also corroborated by the U.S. Consumer Financial Protection Bureau, which in its home loan guide writes: "A mortgage lending rule of thumb is that your total monthly home payment should be at or below 28% of your total monthly income before taxes." (see [Consumer Financial Protection Bureau, 2015](#), p. 5). Since there are no taxes in the model, the labor incomes the households receive should be treated as after tax incomes. The average labor tax rate was 23.1 pct. in the postwar U.S., according to [Jones \(2002\)](#). The DTI limit accordingly becomes  $\frac{0.28}{1-0.231} = 0.36$  for incomes *after taxes*.

Given the calibration of the DTI limit, a steady-state LTV limit of 77 pct. ensures that the borrowing limits imposed by the two constraints are identical in the steady state

<sup>19</sup>[Kaplan et al. \(2017\)](#) similarly set their DTI limit to 25 pct.

**Table 2:** PRIOR AND POSTERIOR DISTRIBUTIONS

Prior Distribution				Posterior Distribution					
Type	Mean	S.D.	Baseline			Only LTV Constraint			
			Mode	5 pct.	95 pct.	Mode	5 pct.	95 pct.	
<b>Structural Parameters</b>									
$\alpha$	B	0.66	0.10	0.5833	0.5605	0.6062	0.2991	0.2943	0.3038
$\beta'$	B	0.984	0.006	0.9892	0.9892	0.9893	0.9871	0.9868	0.9874
$\eta_C$	B	0.70	0.10	0.6218	0.5915	0.6521	0.4890	0.4664	0.5116
$\eta_H$	B	0.70	0.10	0.6591	0.6319	0.6864	0.6699	0.6500	0.6898
$\varphi$	N	5.00	0.15	3.9298	3.4829	4.3767	2.0905	1.9524	2.2287
$\rho$	B	0.25	0.10	0.2029	0.1847	0.2211	0.4102	0.3878	0.4325
$\iota$	N	10.0	2.00	20.805	18.965	22.645	18.586	16.867	20.306
$\tau_R$	B	0.75	0.05	0.7264	0.7054	0.7473	0.6026	0.5803	0.6249
$\tau_P$	N	1.50	0.15	2.0568	1.4940	2.6195	1.7722	1.2840	2.2605
<b>Autocorrelation of Shock Processes</b>									
IP	B	0.50	0.20	0.7829	0.7551	0.8107	0.7939	0.7756	0.8121
HP	B	0.50	0.20	0.9628	0.9487	0.9769	0.9966	0.9943	0.9989
CC	B	0.50	0.20	0.9911	0.9872	0.9950	0.9753	0.9702	0.9803
AY	B	0.50	0.20	0.9701	0.9636	0.9765	0.9643	0.9579	0.9707
LP	B	0.50	0.20	0.9817	0.9778	0.9855	0.9677	0.9613	0.9741
<b>Standard Deviations of Innovations</b>									
IP	IG	0.01	0.10	0.0622	0.0512	0.0733	0.0174	0.0109	0.0240
HP	IG	0.01	0.10	0.0636	0.0524	0.0748	0.0198	0.0129	0.0268
CC	IG	0.01	0.10	0.0144	0.0081	0.0208	0.0088	0.0037	0.0139
AY	IG	0.01	0.10	0.0399	0.0306	0.0492	0.0260	0.0183	0.0337
LP	IG	0.01	0.10	0.0016	0.0001	0.0048	0.0015	0.0001	0.0046
MP	IG	0.01	0.10	0.0094	0.0040	0.0148	0.0096	0.0043	0.0148
<b>Measures of Fit at the Posterior Mode (absolute log values)</b>									
Posterior Kernel				4045.11			4009.95		
Marginal Data Density				4296.98			4266.21		

*Distributions:* N: Normal. B: Beta. IG: Inverse-Gamma.

*Shocks:* IP: Intertemporal preference. HP: Housing preference. CC: Credit. AY: Labor-augmenting technology. LP: Labor preference. MP: Monetary policy.

*Note:* The bounds indicate the confidence intervals surrounding the posterior mode. The prior distribution of  $\beta'$  is truncated with an upper bound at 0.9899.

(cf., the discussion on the solution of the model in Subsection 4.1). This LTV limit is well within the range of typically applied limits (e.g., Liu et al. (2013) and Liu et al. (2016) use 0.75, Kydland et al. (2016) use 0.76, Justiniano et al. (2018) use 0.80, and Iacoviello and Neri (2010) and Justiniano et al. (2015) use 0.85).

Table 2 reports the prior distributions of the estimated parameters. The prior means of the wage share parameter ( $\alpha = 0.66$ ), the impatient time discount factor ( $\beta' = 0.984$ ), the habit formation parameters ( $\eta_C = \eta_H = 0.70$ ), and the debt inertia parameter ( $\rho = 0.25$ ) follow the prior means in Guerrieri and Iacoviello (2017). The prior mean of the elasticity



of the marginal disutility of labor supply ( $\varphi = 5.00$ ) implies a real wage elasticity of labor supply of  $\frac{1}{5}$ , consistent with the micro-estimates in [MaCurdy \(1981\)](#) and [Altonji \(1986\)](#). The prior means of the remaining estimated parameters follow the prior means of the corresponding parameters in [Iacoviello and Neri \(2010\)](#).

## 4.4 Posterior Distribution

Table 2 reports two posterior distributions: One from the baseline model with two occasionally binding credit constraints and one from a model with only an occasionally binding LTV constraint. Apart from not featuring a DTI constraint, this latter model is identical to the baseline model. The difference in marginal data densities across the two models implies a posterior odds ratio of  $\exp(30.8)$  to 1 in favor of the baseline model, suggesting that the data massively favor the baseline model.

The estimates of the wage share parameter ( $\alpha = 0.58$ ), the impatient time discount factor ( $\beta' = 0.9892$ ), and debt inertia ( $\rho = 0.20$ ) in the baseline model are similar to the estimates of the corresponding parameters in [Guerrieri and Iacoviello \(2017\)](#). This is comforting considering that these parameters are decisive in determining when the credit constraints bind. The confidence bounds surrounding the three estimates are considerably smaller than in [Guerrieri and Iacoviello \(2017\)](#). One plausible explanation for this higher precision is that the mortgage debt series, which is intimately related to these parameters, is included in my estimation sample, but not in [Guerrieri and Iacoviello's \(2017\)](#) sample. Another explanation for this is that, while there is the same number of variables and 64 more observations in my estimation sample, as compared to [Guerrieri and Iacoviello's \(2017\)](#) sample, there are two fewer estimated structural parameters.

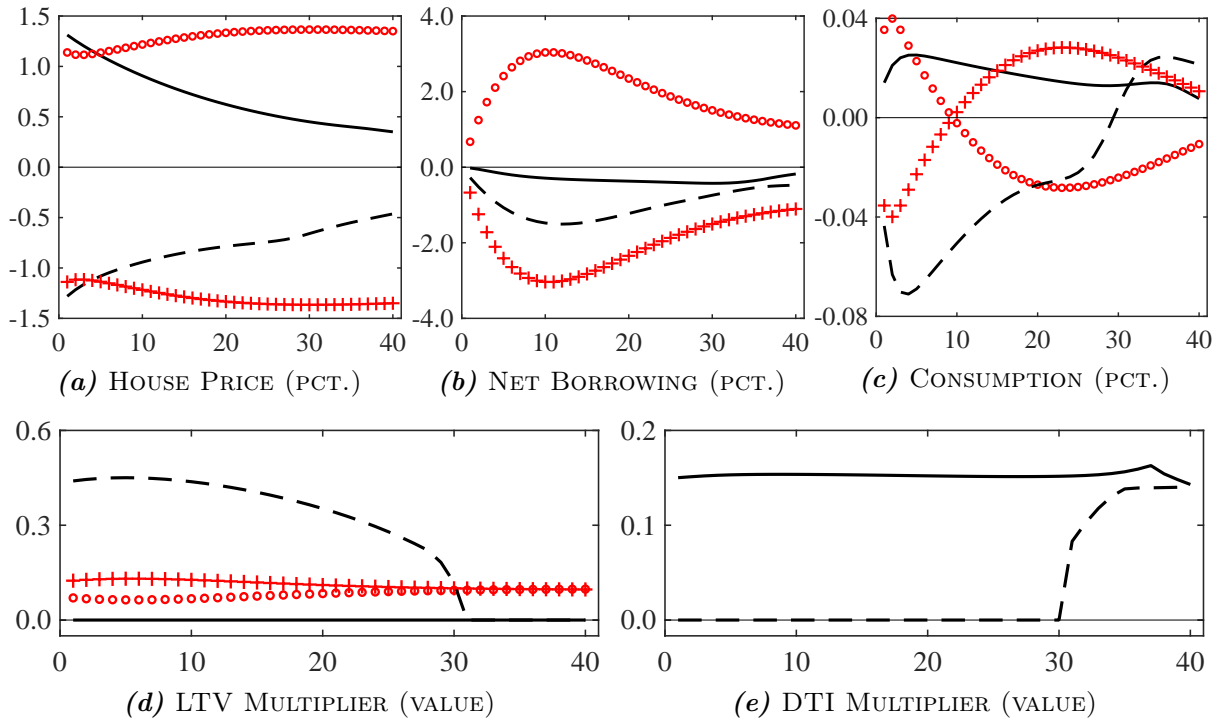
## 5 Asymmetric and State-Dependent Dynamics

This section illustrates how endogenous switching between the credit constraints generates asymmetric and state-dependent responses to housing preference and credit shocks. The section also illustrates that the responses of the model with only an LTV constraint are radically different from the baseline responses. In the LTV model, nonlinearities only arise if the LTV constraint unbinds, which presupposes that borrowing demand is saturated. As we will see, this type of event occurs much more rarely than simple switching between the constraints. Thus, while the LTV constraint might provide some business cycle nonlinearity in expansions, the nonlinearities of the two constraint model apply to a much broader set of scenarios.

Figure 1 plots the effects of unit standard deviation positive and negative housing preference shocks, in the baseline model and in the LTV model. The responses of borrowing and consumption are highly asymmetric in the baseline model and completely symmetric in the LTV model. The asymmetries in the baseline model arise from differences in



**Figure 1: ASYMMETRIC IMPULSE RESPONSES TO HOUSING PREFERENCE SHOCKS**



— Baseline: Positive    - - - Baseline: Negative    ○ LTV Model: Positive    + LTV Model: Negative

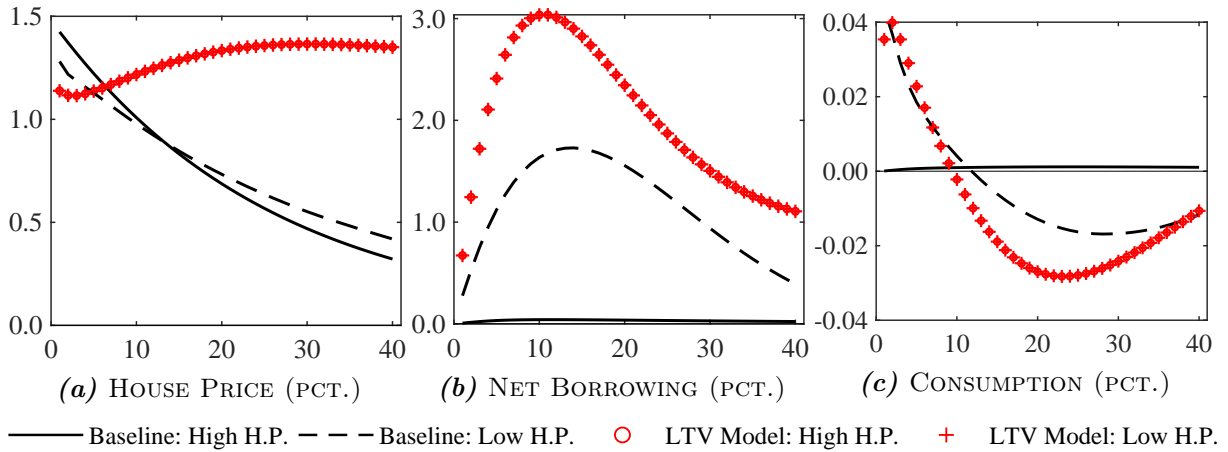
*Note:* The models are calibrated to their respective posterior modes. Vertical axes measure deviations from the steady state (Figures 1a-1c) or utility levels (Figures 1d-1e), following positive and negative unit standard deviation shocks.

the constraint that binds. Following a positive shock, the house price increases. The concurrent increase in borrowers' wealth allows them to consume more goods, leading to a small increase in aggregate consumption. The central bank raises the interest rate, which tightens the DTI constraint, thereby suppressing borrowing and limiting the increase in consumption. Following the negative shock, instead, the house price falls, and the LTV constraint is tightened, inducing the impatient household to reduce consumption, in order to delever proportionally to the drop in housing wealth. The symmetry in the consumption responses match with Engelhardt (1996) and Skinner (1996), showing statistically significant consumption responses to falls in housing wealth, but not to increases.

## 5.1 Responses to Housing Preference Shocks

Next, Figure 2 plots the effects of positive unit standard deviation housing preference shocks, which occur in low and high house price states, in the baseline model and in the LTV model. The house price states are simulated by lowering or raising the housing preference of both households permanently by one standard deviation, before applying the shock impulses. In the baseline model, the housing preference shock only expands borrowing and consumption in the low house price state. This is in contrast to the LTV model, where the housing preference shock expands borrowing and consumption in both

**Figure 2:** STATE-DEPENDENT IMPULSE RESPONSES TO HOUSING PREFERENCE SHOCKS



*Note:* The models are calibrated to their respective posterior modes. The housing preference of both households is permanently one standard deviation below (above) its steady-state level in the low (high) house price state in the absence of the housing preference shocks. Vertical axes measure deviations from these house price states that are caused by the housing preference shocks.

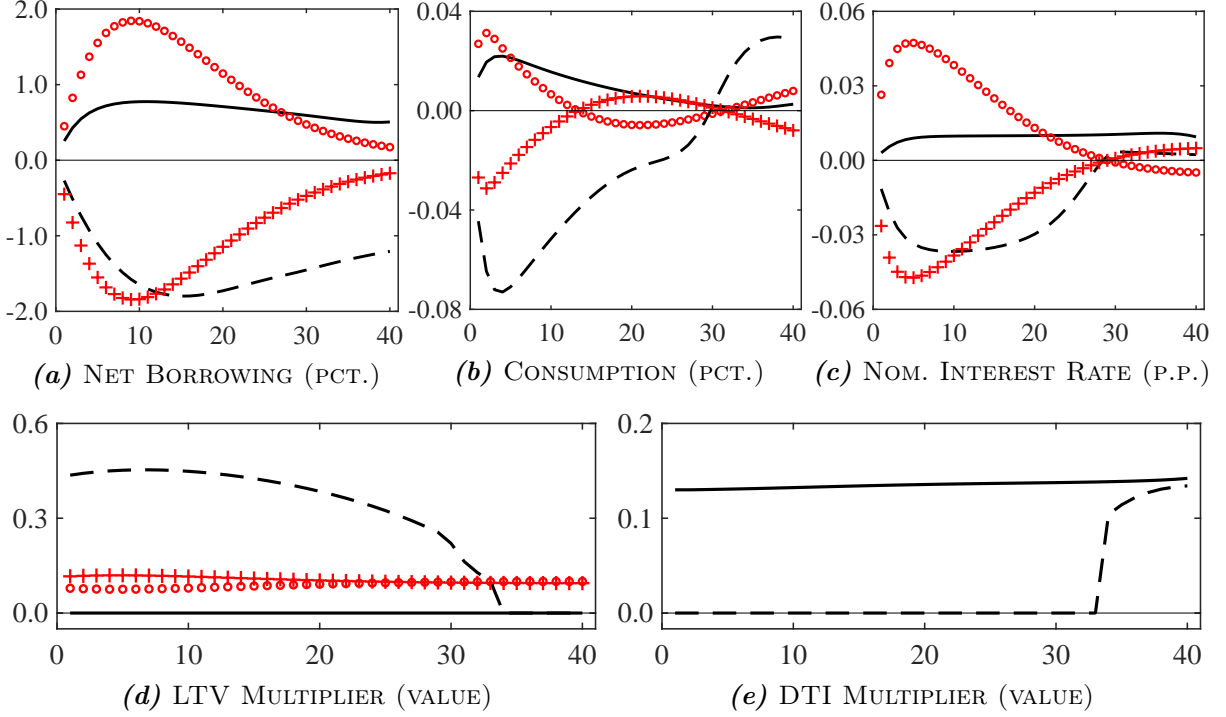
states. The responses in the baseline model are caused by differences across the business cycle in the constraint that binds. When the house price is relatively low and the LTV constraint binds, this constraint forcefully propagates the house price appreciation onto borrowing and consumption. When the house price is already high and the DTI constraint binds, this amplification channel is switched off, significantly muting the effects of the housing preference shock. The state-dependence is in keeping with [Guerrieri and Iacoviello \(2017\)](#), who show that economic activity is considerably more sensitive to house prices in low house price states than in high house price states, and [Prieto et al. \(2016\)](#), who show the same thing for crisis and non-crisis periods.

The symmetric and state-invariant responses in the LTV model, shown in Figures 1-2, arise, since its LTV constraint does not stop binding following the impulses. As a result, borrowing always moves in tandem with housing wealth, leaving the model completely linear. If the constraint were to stop binding, nonlinearities would arise, but they would, in general, be smaller than in the baseline model. The differences between the two models suggest that frameworks with only an LTV constraint misidentify the propagation from lone housing preference shocks.

## 5.2 Responses to Credit Shocks

Figure 3 now plots the effects of unit standard deviation positive and negative credit shocks, in the baseline model and in the LTV model. A positive shock causes borrowing and consumption to increase, while a negative shock causes borrowing and consumption to fall, in both models. However, the size of the responses is highly asymmetric to the sign of the shock in the baseline model and completely symmetric in the LTV model. More precisely, in the baseline model, borrowing and consumption move over three times

*Figure 3: ASYMMETRIC IMPULSE RESPONSES TO CREDIT SHOCKS*



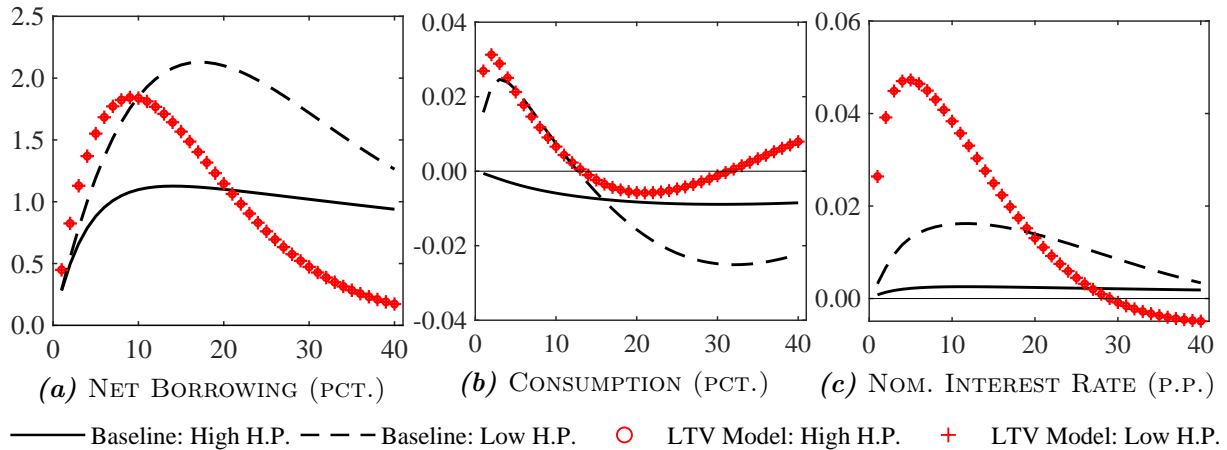
— Baseline: Positive    - - - Baseline: Negative    O LTV Model: Positive    + LTV Model: Negative

*Note:* The models are calibrated to their respective posterior modes. Vertical axes measure deviations from the steady state (Figures 3a-3c) or utility levels (Figures 3d-3e), following positive and negative unit standard deviation shocks.

more when a negative shock occurs, as compared to a positive one, measured at the peak of the responses. This degree of asymmetry is commensurate to [Barnichon et al. \(2017\)](#), who show that the effects of adverse bond premium shocks are four times larger than the effects of favorable shocks. Moreover, the asymmetry is consistent with [Kuttner and Shim \(2016\)](#), who find significant negative effects of LTV and DTI tightenings on household credit and insignificant positive effects of relaxations, using a sample of 57 economies across 1980-2012. The asymmetries in the baseline model again result from differences in the constraint that binds. Following the positive shock, consumption and housing demand rise, along with house prices and inflation. However, the ensuing rise in the interest rate tightens the DTI constraint, thus moderating the increase in credit and consumption. Following the negative shock, the impatient household is conversely forced to delever, leading it to cut consumption and housing demand. This latter response and the associated drop in house prices tighten the LTV constraint, and amplify the contraction in credit and consumption.

Finally, [Figure 4](#) plots the effects of positive unit standard deviation credit shocks, which occur in low and high house price states, in the baseline model and the LTV model. The house price states are again generated by permanent housing preference shocks. In the baseline model, the responses are state-dependent, with the sign of the consumption

*Figure 4: STATE-DEPENDENT IMPULSE RESPONSES TO CREDIT SHOCKS*



*Note:* The models are calibrated to their respective posterior modes. The housing preference of both households is permanently one standard deviation below (above) its steady-state level in the low (high) house price state. Vertical axes measure deviations from these house price states that are caused by the credit shocks.

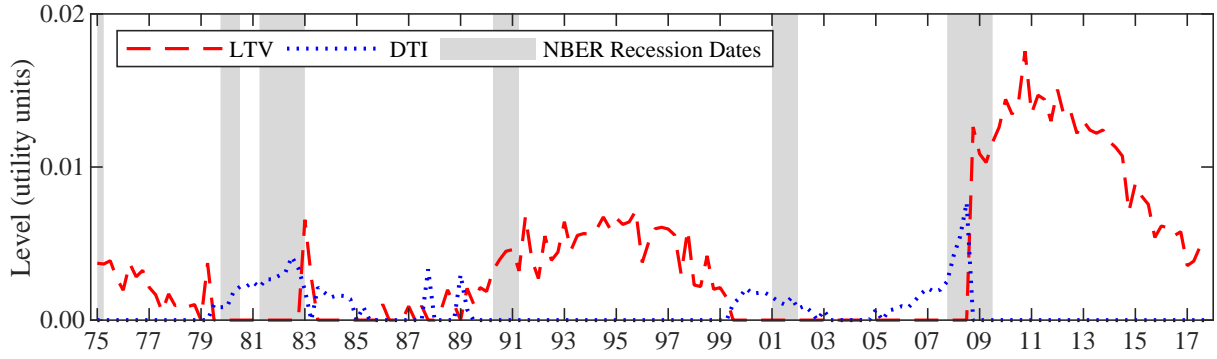
response varying between states. Once again, these baseline responses are qualitatively comparable to [Barnichon et al. \(2017\)](#), who find that favorable bond premium shocks have positive effects on output in contractions and no effects in expansions. These responses again contradict the LTV model, in which borrowing and consumption expand by the same amount between states. The state-dependent responses are caused by differences, across the house price cycle, in the constraint that binds. A positive credit shock always increases consumption, inflation, and thus leads the central bank to hike the interest rate. Furthermore, the impatient household always increases its housing demand. When the house price is relatively low and the LTV constraint binds, the concurrent house price appreciation amplifies the leveraging process, leading to a further increase in aggregate consumption. By contrast, when the house price is high and the DTI constraint binds, the higher interest rate curbs the increase in borrowing and consumption of the impatient household to the extent that aggregate consumption falls.

As for the LTV model, we again observe symmetric and state-invariant responses, due to the LTV constraint not becoming slack.

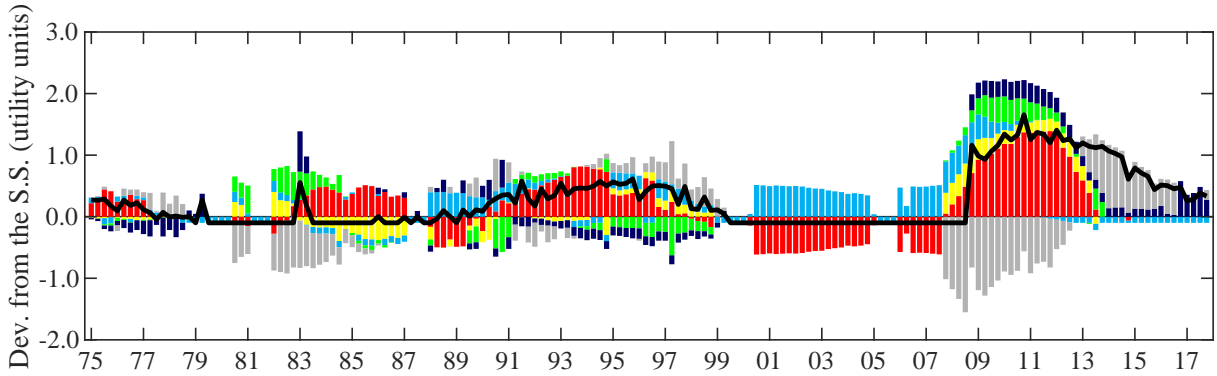
## 6 The Historical Evolution in Credit Conditions

This section gives a historical account of the evolution in credit conditions. The first subsection focuses on when each credit constraint restricted mortgage borrowing, and the circumstances that led them to do so. The second subsection zooms in on the importance of credit shocks in exogenously shifting LTV and DTI limits.

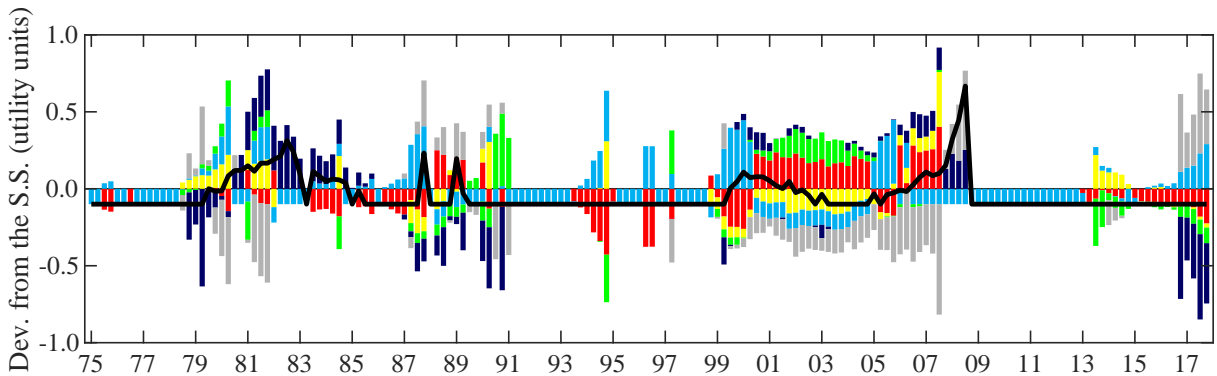
Figure 5: SMOOTHED POSTERIOR VARIABLES



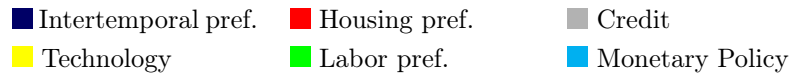
(a) LAGRANGE MULTIPLIERS



(b) SHOCK DECOMPOSITION OF LTV LAGRANGE MULTIPLIER



(c) SHOCK DECOMPOSITION OF DTI LAGRANGE MULTIPLIER



Note: The decomposition is performed at the baseline posterior mode. Each bar indicates the contribution of a given shock to a certain variable. The shocks were marginalized in the following order: (1) housing preference, (2) labor-augmenting technology, (3) monetary policy, (4) labor preference, (5) credit, and (6) intertemporal preference. The results are robust to alternative orderings.

## 6.1 LTV vs. DTI Constraints

Figure 5a superimposes the smoothed posterior Lagrange multipliers of the two credit constraints onto shaded NBER recession date areas. The LTV constraint binds when  $\lambda_{LTV} > 0$ , while the DTI constraint binds when  $\lambda_{DTI} > 0$ . Figures 5b-5c plot the histori-

cal shock decomposition of the Lagrange multipliers in deviations from the steady state.<sup>20</sup> At least one Lagrange multiplier is positive through most of the period 1975-2017. Borrowers have thus been credit constrained through most of the considered timespan. The LTV constraint often binds during and after recessions, and the DTI constraint mostly binds in expansions. This pattern largely reflects that house prices are more volatile than personal incomes, so that, in recessions, the LTV constraint is tightened more than the DTI constraint. This latter point is accentuated by a negative skewness in the house price growth rate, signifying that, once house prices have fallen, they do not rise quickly again.<sup>21</sup> Lastly, the pattern is also due to countercyclical monetary policy, which, *ceteris paribus*, relaxes the DTI constraint in recessions and vice versa in expansions.

In the end-1970s, the oil crises and the resulting stagflation depressed the real house price to the extent that the LTV constraint was binding. Starting from 1980, the DTI constraint became binding, partly as the tight monetary policy of Paul Volcker dramatically increased interest payments, and partly as low productivity growth, poor employment prospects, and depressed consumer sentiments (negative intertemporal preference shocks) curtailed goods demand and cut incomes. Eventually, however, from around 1983, the DTI constraint was gradually relaxed. This relaxation broadly stemmed from the mid-1980s boom and the onset of the Great Moderation, which led to economic optimism (antecedent negative intertemporal preference shocks disappearing) and lower mortgage rates, in addition to increased productivity growth. As a result, both constraints ended up periodically not binding in 1985-1986. Thus, the U.S. entered the first period in recent history where mortgage issuance was determined by the loan demand of the borrowers, rather than by credit restrictions. Later on, from 1989 and through the early-1990s recession, the LTV constraint again started to lastingly bind, as mortgage rates were hiked, house prices fell, and credit limits were tightened. Then, from 1999 and into the mid-2000s economic boom, the DTI constraint became binding. Initially, a more hawkish monetary policy and weak employment opportunities increased interest payments and lowered incomes, while a gradual house price growth simultaneously relaxed the LTV constraint. From 2003, however, the U.S. would enter the second period where mortgage issuance was demand-determined, as booming productivity growth, along with lax credit limits and a dovish monetary policy, also caused the DTI constraint to unbind. Later, from 2005, the DTI constraint would again bind, due to a dwindling wage and house price growth, in addition to depressed consumer sentiments. With the onset of the Great Recession, the LTV constraint started to bind, and continued doing so for the remaining part of the sample, as house prices plummeted and credit conditions gradually deteriorated.

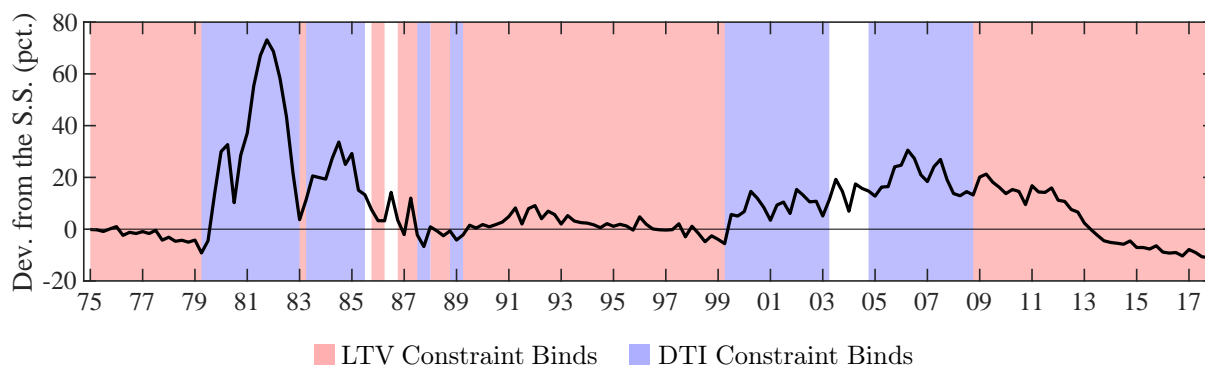
The shock decomposition echoes the result of [Guerrieri and Iacoviello \(2017\)](#) that the LTV constraint was slack in 1999-2007, due to soaring house prices. However, in contrast

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<sup>20</sup>The steady-state values of the Lagrange multipliers are positive and identical, since both constraints are binding in the steady state.

<sup>21</sup>The volatilities of the detrended house price and personal income series are 0.091 and 0.019. The skewness of the growth rate of the detrended house price series is  $-0.88$ .

*Figure 6: SMOOTHED CREDIT SHOCK*



*Note:* The historical credit shock is identified at the baseline posterior mode. At a given point in time, the shock is identified through the constraint that allows for the lowest amount of borrowing, as discussed in Subsection 4.1.

to their findings, the decomposition also shows that this did not imply that homeowners were free to borrow. Instead, they remained constrained by debt service requirements, with the exception of 2003-2004.

## 6.2 Credit Limit Cycles

This subsection focuses on how historical events have shifted LTV and DTI limits exogenously. Figure 6 superimposes the smoothed posterior credit shock ( $s_{C,t}$ ) onto shaded areas indicating when each credit constraint has been binding. The U.S. economy has undergone two credit boom-busts in the past 43 years.

The first credit cycle started in the early-1980s. Credit limits were raised 53 pct. above their steady-state levels, on average across 1981-1982. This implies that the binding DTI limit was raised from its steady-state limit of 28 pct. before taxes in 1979 to 43 pct. This relaxation likely resulted from the first major financial deregulation since the Great Depression. The Depository Institutions Deregulation and Monetary Control Act of 1980 and the Garn-St. Germain Depository Institutions Act of 1982 deregulated and increased the competition between banks and thrift institutions, according to [Campbell and Hercowitz \(2009\)](#). In addition, state deregulation allowed banks to expand their branch networks within and between states, further increasing bank competition, as emphasized by [Mian et al. \(2017\)](#). Due to these changes in legislation, greater access to alternative borrowing instruments (e.g., adjustable-rate loans) reduced effective down payments and allowed households to delay repayment through cash-out refinancing. This process continued until the Black Monday Stock Market Crash of 1987 and the Savings and Loan Crisis, after which credit limits returned to their steady-state levels.

The second credit cycle started in 1999. This time, credit limits were raised 26 pct. above their steady-state levels, by 2006. This implies that the DTI limit, which was binding in 1999-2002 and 2005-2008, was raised to 35 pct. These observations are consistent with [Justiniano et al. \(2017, 2018\)](#), who find that looser LTV limits cannot explain the recent



credit boom, and that the fraction of borrowers presenting full income documentation dropped substantially in 2000-2007. [Justiniano et al. \(2018\)](#) also argue that it was an increase in credit supply which caused the surge in mortgage credit. They mention the pooling and tranching of mortgage bonds into mortgage-backed securities and the global savings influx into the U.S. mortgage market following the late-1990s Asian financial crisis. These discoveries are consistent with my result that the DTI limit was relaxed, since it suggests that the increase in credit supply translated into a relaxation of the DTI limit.<sup>22</sup> Later on, from the eruption of the Subprime Crisis in 2007 and into the ensuing recession, credit limits were gradually tightened, and eventually fell below their steady-state levels. The absence of a rapid tightening around 2009 possibly reflects the introduction of the Home Affordable Refinance Program and the Home Affordable Modification Program in March 2009. These programs lowered the debt services for homeowners who had high LTV ratios or were in delinquency, via an exemption from mortgage insurance, interest rate and principal reductions, forbearance, and term extensions. Waves of mortgage defaults were thereby avoided, according to [Agarwal, Amromin, Chomsisengphet, Landvoigt, Piskorski, Seru, and Yao \(2015\)](#) and [Agarwal, Amromin, Ben-David, Chomsisengphet, Piskorski, and Seru \(2017\)](#), allowing for a more gradual subsequent deleveraging.

The overall validity of the shock estimates in Figure 6 is corroborated by [Prieto et al. \(2016\)](#), who also find traces of two credit cycles, using a VAR approach.

## 7 Macprudential Policy Implications

Recent studies show that credit expansions predict subsequent banking and housing market crises with severe economic consequences (e.g., [Mian and Sufi, 2009](#); [Schularick and Taylor, 2012](#); [Baron and Xiong, 2017](#)). Motivated by this, I will now examine how mortgage credit would historically have evolved if LTV and DTI limits had responded countercyclically to deviations of credit from its long-run trend. Figure 7a plots the reaction of borrowing to the estimated sequence of shocks under four different macroprudential regimes. In the first regime, there is no active macroprudential policy, so the credit limits are only shifted by the credit shock, as in the estimated model. Thus, the observed variables in the model, by construction, match the data. In the three other regimes, the following policies apply: a countercyclical LTV limit, a countercyclical DTI limit, and countercyclical LTV and DTI limits. Figures 7b-7c plot the credit limits implied by the policies. I introduce the countercyclical debt limits by augmenting the credit constraints

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<sup>22</sup>Credit constraints are, in the model, the only wedges between the credit supply of the patient household and the credit demand of the impatient household. Hence, the credit shock, in a reduced form, captures all exogenous shocks to both credit supply and credit demand.



in (5) and (6) with two macroprudential stabilizers:

$$b'_t \leq (1 - \rho) \frac{b'_{t-1}}{1 + \pi_t} + \rho \xi_{LTV} s_{LTV,t} \mathbb{E}_t \left\{ (1 + \pi_{t+1}) q_{t+1} h'_t \right\},$$

$$b'_t \leq (1 - \rho) \frac{b'_{t-1}}{1 + \pi_t} + \rho \xi_{DTI} s_{DTI,t} \mathbb{E}_t \left\{ \frac{(1 + \pi_{t+1}) w'_{t+1} l'_t}{\sigma + r_t} \right\},$$

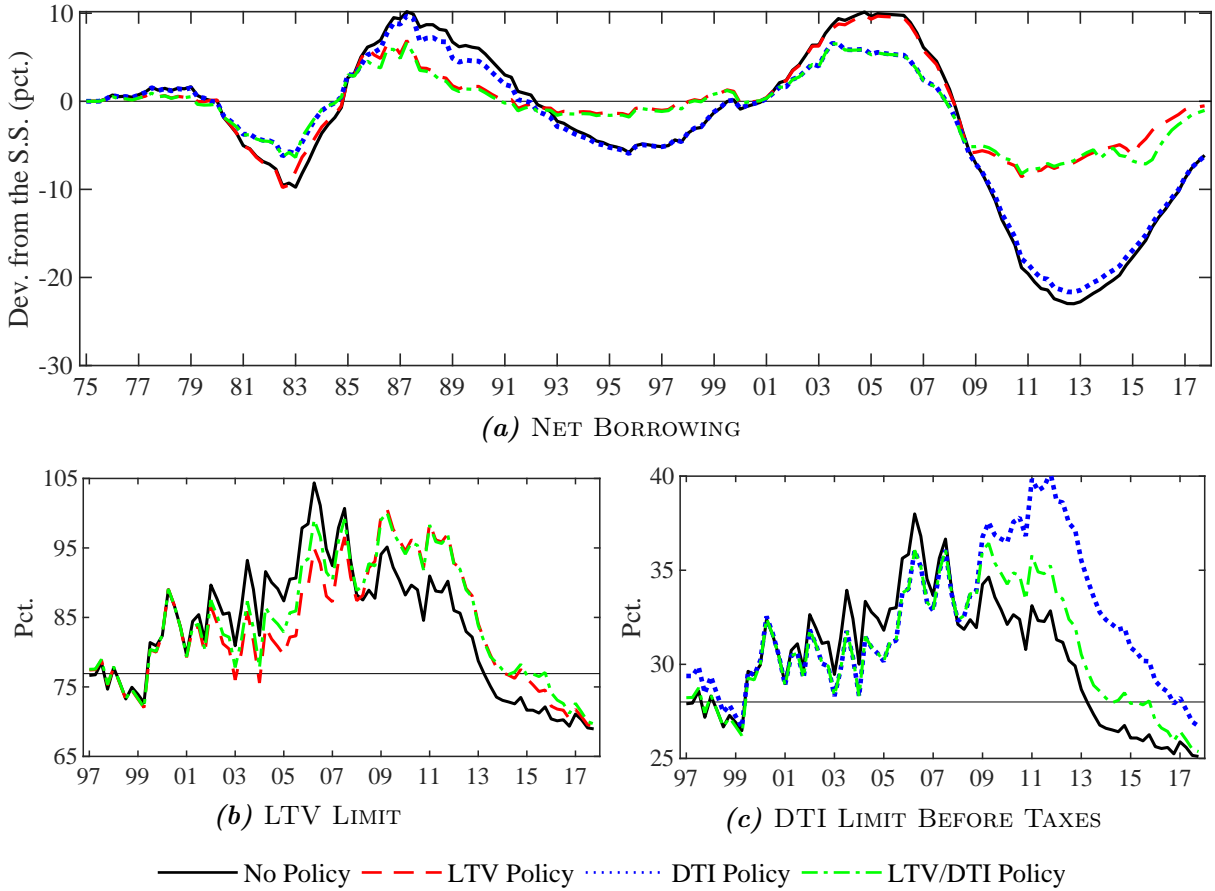
where  $s_{LTV,t}$  is an LTV stabilizer, and  $s_{DTI,t}$  is a DTI stabilizer. As the simplest imaginable policy rule to stabilize credit, the stabilizers respond negatively with a unit elasticity to deviations of borrowing from its steady-state level:

$$\log s_{LTV,t} = -(\log b'_t - \log b') \quad \text{and} \quad \log s_{DTI,t} = -(\log b'_t - \log b'), \quad (15)$$

where  $b'$  denotes steady-state net borrowing. Numerous other functional forms than the ones in (15) are, in principle, conceivable to capture countercyclical macroprudential policy. In Appendix F, I try a rule that also has some persistence, as well as a rule that responds negatively to the quarterly year-on-year growth in borrowing. The policy considerations provided in the text below also apply in these alternative cases.

The historical standard deviation of borrowing is 8.9 pct. The LTV policy reduces this standard deviation to 4.7 pct., i.e., by 48 pct. relative to the historical benchmark. It does so mostly by mitigating the adverse effects of house price slumps on credit availability when the LTV constraint is binding. For instance, following the Great Recession, the LTV limit is, on average, 6.6 p.p. higher under (15) than in the benchmark simulation, which considerably limits the credit bust. The flip-side of this result is that the LTV policy often cannot curb credit expansions during house price booms, since the LTV constraint is slack there. Thus, even though the LTV limit, on average across 2003-2006, is 7.7 p.p. lower with the LTV policy, as compared to the benchmark simulation, macroprudential policy does not prevent the mid-2000s boom in credit. The DTI policy is, by contrast, able to curb credit during house price booms by enforcing stricter DTI limits. In the above simulations, this policy reduces the standard deviation of borrowing to 7.8 pct., i.e., by 12 pct. relative to the benchmark. In this way, while the DTI policy has a smaller quantitative effect on mortgage borrowing than the LTV policy, the fact that it curtails credit expansions makes it particularly useful. Zooming in on the mid-2000s credit boom, the DTI policy dictates that the DTI limit should have been 1.8 p.p. lower, again on average across 2003-2006. This would roughly have halved the expansion in credit from 1999 to 2006. The lowest volatility in borrowing is reached by combining the LTV and DTI policies. This reduces the standard deviation of borrowing to 3.8 pct., i.e., by 58 pct. relative to the benchmark. In this case, macroprudential policy takes into account that the effective policy tool changes over the business cycle, mostly with a DTI tool in expansions and an LTV tool in contractions. The implementation of such a policy does not require that the policymaker in real time knows when either constraint binds. Rather, it merely presupposes that the policymaker conducts a two-stringed policy entailing that

Figure 7: ALTERNATIVE MACROPRUDENTIAL REGIMES

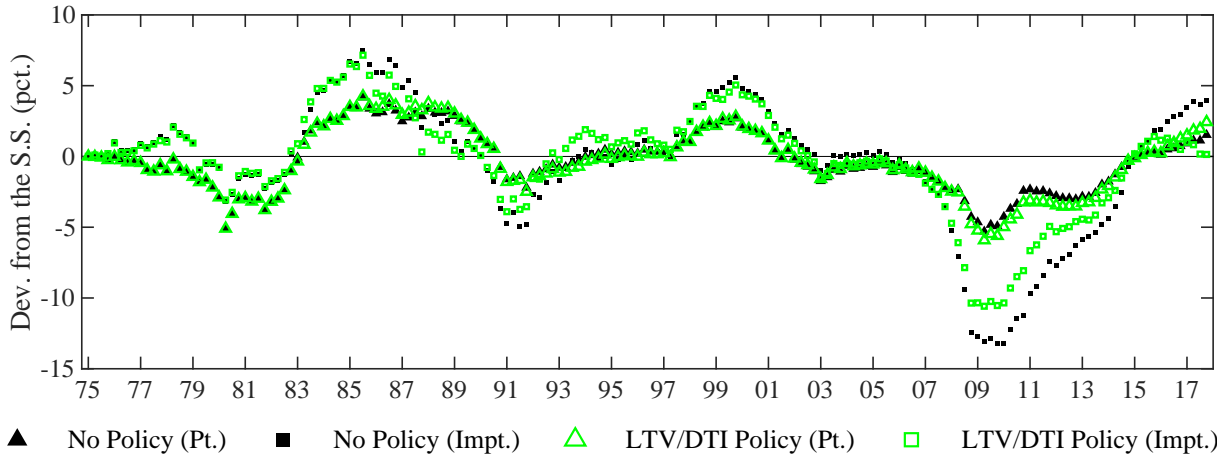


Note: The simulations are performed at the baseline posterior mode. Figures 7b-7c plot  $\xi_{LTV}^{SC,t}$  and  $\xi_{DTI}^{SC,t}$ , with horizontal lines indicating  $\xi_{LTV}$  and  $\xi_{DTI}$ .

both LTV and DTI limits respond countercyclically to credit growth.

The underlying objective of a macroprudential policy that stabilizes credit fluctuations is arguably to minimize the probability of large drops in consumption. For this reason, I now compute a measure of consumption-at-risk in the no-policy scenario and under the two-stringed policy. I define consumption-at-risk as the maximum negative deviation of consumption from its steady-state level occurring within the top 95 pct. of the distribution of consumption observations. Such a definition is congruous with the value-at-risk measure commonly used within finance and the output-at-risk measure of Nicolò and Lucchetta (2013) and Jensen et al. (2018). Historical consumption-at-risk is 3.7 pct. of steady-state consumption for the patient household and 11.1 pct. for the impatient household. Under the two-stringed policy, consumption-at-risk increases to 4.1 pct. for the patient household, and decreases to 8.1 pct. for the impatient household. Figure 8 sheds some light on these changes by plotting the paths of household consumption in the two scenarios. Under the active policy, deleveraging in busts is significantly curtailed, as was previously shown by Figure 7. This dampens the redistribution of funds from the impatient to the patient household in these episodes, leaving borrowers able to consume more and lenders

**Figure 8:** ALTERNATIVE MACROPRUDENTIAL REGIMES: HOUSEHOLD CONSUMPTION



*Note:* The simulations are performed at the baseline posterior mode.

necessitated to consume less. As a result, the left tail of the consumption distribution is lower for the patient household and higher for the impatient household. The two-stringed policy thus redistributes consumption *risk* from the impatient household to the patient household, while roughly maintaining average household consumption levels.<sup>23</sup> Aggregate consumption and output are roughly unaffected by the policy, because the responses of borrowers and lenders "wash out in the aggregate", as coined by Justiniano et al. (2015).

The benefits of a two-stringed macroprudential policy are not well-documented within economics. With the exception of Greenwald (2018), who focuses on policy counterfactuals around the Great Recession, there is little theoretical guidance on how to combine the two limits, as also noted by Jácome and Mitra (2015). Instead, the existing literature focuses on stabilization through countercyclical LTV limits.<sup>24</sup> The ineffectiveness of LTV limits in expansions and DTI limits in contractions underscores the necessity of models with both constraints in order to determine the optimal implementation of macroprudential policy.

## 8 Evidence on State-Dependent Credit Origination

The credit constraints predict that house price (income) growth shall not allow homeowners to take on additional debt if incomes (house prices) are below a certain threshold. In this section, I test this prediction by estimating the elasticities of mortgage loan origination with respect to house prices and personal incomes, importantly after partitioning the house price (income) elasticity based on the detrended income (house price) level.

<sup>23</sup>Consumption is 0.06 pct. lower in the patient household and 0.21 pct. higher in the impatient household, on average across 1975-2017.

<sup>24</sup>See, e.g., the Committee on the Global Financial System (2010), the IMF (2011), Lambertini, Mendicino, and Teresa Punzi (2013), and Jensen et al. (2018). In addition to these contributions, Gelain, Lansing, and Mendicino (2013) show that loan-to-income constraints are more effective than LTV constraints at stabilizing mortgage borrowing in both booms and busts, using a linear model with a single always binding constraint.

**Table 3:** SUMMARY STATISTICS OF GROWTH RATES (2008-2016)

Counts, Means, and Standard Deviations by Year							
Variable	Obs.	Loan Origination		House Price		Disp. Personal Income	
		Mean	S.D.	Mean	S.D.	Mean	S.D.
2008	2643	-0.339	0.258	0.043	0.038	0.043	0.038
2009	2656	0.193	0.216	-0.030	0.038	-0.030	0.038
2010	2657	-0.118	0.128	0.030	0.026	0.030	0.026
2011	2667	-0.092	0.108	0.058	0.028	0.058	0.028
2012	2666	0.345	0.140	0.046	0.033	0.046	0.033
2013	2663	-0.085	0.120	0.013	0.025	0.013	0.025
2014	2664	-0.297	0.124	0.050	0.026	0.050	0.026
2015	2649	0.253	0.104	0.048	0.026	0.048	0.026
2016	2631	0.152	0.086	0.023	0.021	0.023	0.021
All years	23896	0.003	0.275	0.031	0.039	0.031	0.039

Correlations across all Years			
	Loan Origination	House Price	Disp. Personal Income
Loan Origination	1.00		
House Price	0.22	1.00	
Disp. Personal Income	-0.06	0.31	1.00

*Note:* The observations are weighted by the county population in a given year.

## 8.1 Data

The dataset contains data on the amount of originated mortgage loans, house prices, and personal incomes, across U.S. counties in all 50 states and the District of Columbia at an annual longitudinal frequency. The data on originated mortgage loans is from the Home Mortgage Disclosure Act (HMDA) dataset of the U.S. Consumer Financial Protection Bureau. This dataset is also used by [Mondragon \(2018\)](#) and [Gilchrist, Siemer, and Zakrajšek \(2018\)](#) to study the effects of credit supply shocks to households. I consider originated mortgage loans that are secured by a first or subordinate lien in an owner-occupied principal dwelling, consistent with the theoretical measure of credit in the DSGE model. The results are robust to broader credit measures, such as total originated mortgage loans. A limitation of the HMDA data is its inability to exactly identify equity extraction. However, as shown by [Mondragon \(2018\)](#), the behavior of aggregate mortgage origination is similar to that of aggregate equity extraction. Coverage of the online HMDA dataset starts in 2007. The house price data is from the All-Transactions House Price Index of the U.S. Federal Housing Finance Agency, and is available from 1975. The income and population data is from the Personal Income, Population, Per Capita Personal Income (CA1) table in the Regional Economic Accounts of the U.S. Bureau of Economic Analysis, and is available from 1966. Since I am regressing log-differences, which entails me to lose the first year of observations, the merged sample effectively covers the 2008-2016 timespan. The dataset is unbalanced, since observations on loan originations and house prices are sporadically missing if the transaction volume in a given county and year was insufficient.

Panel 3 reports summary statistics of the data. The dataset contains 23,896 unique county-year observations on population size and the growth rates of mortgage loan origination, house prices, and incomes. Across the years, there is a substantial variation in both the central tendency and the dispersion of the growth rates of mortgage loan origination, house prices, and incomes. Loan origination growth has a positive correlation with house price growth and a tiny negative correlation with income growth, while house price and income growth are themselves positively correlated.

## 8.2 Identification Strategy

The goal of the analysis is to identify the causal effects of house price growth, income growth, and interactions between house price and income growth on loan origination growth. A challenge to doing this is that house prices and incomes are endogenously determined by each other, along with forces determining home credit. For instance, a favorable credit or productivity shock may increase loan origination, house prices, and incomes without any causal relationship between these variables. In that case, would not only the house price and income elasticities be positively biased, but the interacting effect of house price and income growth would also be positively biased.

In order to overcome the described identification challenge, I rely on an instrumental variable strategy, in combination with a rich set of fixed effects. The instrumental variable strategy uses systematic differences in the sensitivity of local house prices (incomes) to the nationwide house price (income) cycle to instrument house price (income) variation. This strategy is inspired by the commonly used "Bartik instrument", which in labor economics involves using nationwide employment to instrument local labor demand (e.g., [Blanchard and Katz, 1992](#)). [Guren et al. \(2018\)](#) similarly use regional house price cycles to instrument local house prices, in their study of the effect of local house prices on retail employment. For each county  $i$ , I perform the following first-stage time series estimations:

$$\Delta \log hp_{i,t} = \gamma_{i, hp} + \beta_{i, hp} \Delta \log hp_{-i,t} + v_{i,t, hp}, \quad (16)$$

$$\Delta \log inc_{i,t} = \gamma_{i, inc} + \beta_{i, inc} \Delta \log inc_{-i,t} + v_{i,t, inc}, \quad (17)$$

where  $\mathbb{E}\{v_{i,t, hp}\} = \mathbb{E}\{v_{i,t, inc}\} = 0$ .  $\Delta \log hp_{i,t}$  and  $\Delta \log inc_{i,t}$  denote the log-change in house prices and personal incomes in county  $i$  in year  $t$ . Moreover,  $\Delta \log hp_{-i,t}$  and  $\Delta \log inc_{-i,t}$  denote the log-change in the nationwide house prices and personal incomes in year  $t$  after weighing out the contribution of county  $i$  to the nationwide indices.<sup>25</sup> I use the predicted values from (16) and (17) as instruments for the growth rates of house prices and personal incomes across counties.

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<sup>25</sup>This weighing-out is meant to remove the mechanical contribution of county  $i$  to the nationwide indices. I use the county population shares as weights. For all practical purposes, the transformed indices are identical to the nationwide indices, as the population shares of even large counties are tiny. The results are thereupon robust to simply using the nationwide indices as instruments.

In addition to instrumenting house price and income growth, I rely on county and state-year fixed effects, in order to control for potential confounders, as in [Cloyne et al. \(2017\)](#). County fixed effects control for fixed differences in the propensity to originate loans, while state-year fixed effects control for time-varying state shocks to loan origination. Identification hence arises from time-varying differences in credit originations across counties that cannot be explained by the average originations within a county's state. With these controls, e.g., state fiscal or credit shocks will not threaten identification, as they will be captured by the state-year effects.

Under the following two assumptions, a regression of the house price and income instruments on credit originations identifies the causal effects of local house price and income growth on local credit originations. First, the nationwide house price and income cycles must yield predictive power over local house prices and incomes, so that the instruments are relevant.<sup>26</sup> Second, the nationwide house price and income cycles must not be influenced by *local* shocks to credit originations conditional on the fixed effects, implying that the instruments are exogenous.

### 8.3 Results

The baseline second-stage regression specification is given by

$$\begin{aligned} \Delta \log d_{i,t} = & \delta_i + \zeta_{j,t} + \beta_{hp} \Delta \widehat{\log hp}_{i,t-1} + \beta_{inc} \Delta \widehat{\log inc}_{i,t-1} \\ & + \tilde{\beta}_{hp} \mathcal{I}_{i,t}^{inc} \Delta \widehat{\log hp}_{i,t-1} + \tilde{\beta}_{inc} \mathcal{I}_{i,t}^{hp} \Delta \widehat{\log inc}_{i,t-1} + u_{i,t}, \end{aligned} \quad (18)$$

where  $\mathbb{E}\{u_{i,t}\} = 0$ .  $\Delta \log d_{i,t}$  denotes the log-change in the amount of originated mortgage loans in county  $i$  in year  $t$ . Moreover,  $\delta_i$  denotes the county fixed effect in county  $i$ , and  $\zeta_{j,t}$  denotes the state-year fixed effect in state  $j$  in year  $t$ . Finally,  $\Delta \widehat{\log hp}_{i,t}$  and  $\Delta \widehat{\log inc}_{i,t}$  denote the predicted values from (16) and (17). (18) uses lagged house price and incomes variables, so as to prevent any confounding shocks that have not already been instrumented out or are captured by the fixed effects from biasing the results, as in [Guerrieri and Iacoviello \(2017\)](#). The results below are qualitatively robust to a number of alternative econometric assumptions, such as not using the Bartik-instruments, as well as using current house price and income variables. They are also robust to omitting the county fixed effects or replacing the state-year fixed effects with year fixed effects.

In my baseline specification, I let  $\mathcal{I}_{i,t}^{hp}$  and  $\mathcal{I}_{i,t}^{inc}$  denote level indicators for house prices and personal incomes in county  $i$  in year  $t$ . The indicators take the value "1" if the log-level of their input variable is above its long-run county-specific time trend, and the value

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<sup>26</sup>In (16)-(17), the restrictions  $\beta_{i, hp} = 0$  or  $\beta_{i, inc} = 0$  are rejected at a one percent confidence level in 84 pct. of all counties for house prices and 97 pct. for incomes, indicating that the instruments are broadly relevant. The average t-statistic is 5.28 for house prices and 9.69 for incomes across all counties.

"0" if it is below:

$$\mathcal{I}_{i,t}^{hp} \equiv \begin{cases} 0 & \text{if } \log hp_{i,t} \leq \overline{\log hp_{i,t}} \\ 1 & \text{else,} \end{cases} \quad \mathcal{I}_{i,t}^{inc} \equiv \begin{cases} 0 & \text{if } \log inc_{i,t} \leq \overline{\log inc_{i,t}} \\ 1 & \text{else,} \end{cases} \quad (19)$$

where  $\overline{\log hp_{i,t}}$  and  $\overline{\log inc_{i,t}}$  denote separately estimated county-specific log-linear time trends. With this specification, the level indicators partition the house price and income elasticities in (18) based on the prevailing detrended income and house price levels. The house price elasticity given that incomes are low is  $\beta_{hp}$ , while the house price elasticity given that incomes are high is  $\beta_{hp} + \tilde{\beta}_{hp}$ . Consistently, the income elasticity given that house prices are low is  $\beta_{inc}$ , and the income elasticity given that house prices are high is  $\beta_{inc} + \tilde{\beta}_{inc}$ . More forces than just multiple credit constraints could, in principle, cause house price and income growth to amplify each other.<sup>27</sup> Nonetheless, this partitioning does provide a test of whether the state-dependent credit dynamics imposed by the LTV and DTI constraints are present in the data. If homeowners must fulfill a DTI requirement and incomes are currently low, then the house price elasticity should likely be lower than if incomes are high. Likewise, if homeowners must fulfill an LTV requirement and house prices are currently low, then the income elasticity should likely be lower than if house prices are high.

Table 4 reports the ordinary least squares estimates of the second-stage regression in (18) under (19). In specification 1, I do not allow for state-dependent elasticities, in which case only the house price elasticity is significantly positive. In specification 2, I partition the elasticities as explained above, based on trends that were estimated over the period 1975-2016, consistent with the DSGE sample. While the point estimates of the unconditional elasticities do not change to any considerable extent, the estimates of both newly introduced conditional elasticities are significantly positive and, as compared to the unconditional elasticities, sizable. In particular, in the parsimonious specification 3, the house price elasticity is three times greater when incomes are high (1.20) than when they are low (0.38), while the income elasticity (0.41) is only positive when house prices are high. In specifications 4-5, I rerun the estimation, using trends that were computed over the shorter period 2000-2016. These trends plausibly better capture the true trends in house price and income growth around the time that is covered by the full panel sample (2008-2016), since the trend growth rates are unlikely to have been constant over the entire period 1975-2016.<sup>28</sup> The previous results on state-dependent elasticities now appear even more distinctly. In specification 4, both unconditional elasticities shrink markedly towards zero, and become statistically insignificant, so that only house price growth conditional on high incomes and income growth conditional on high house prices increase loan origination.

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<sup>27</sup>For instance, income growth might cause homeowners to be more optimistic about their personal finances, leading them to borrow more as house price growth relaxes LTV constraints.

<sup>28</sup>For instance, shifts in total factor productivity growth, relative sectoral productivity levels, labor market participation, or migration patterns could affect the trend growth rates.



**Table 4:** DETERMINANTS OF CREDIT ORIGINATION: LEVEL SHIFTERS (2008-2016)

Sample Period for Trends	$\Delta \log b_t$					
	N/A	1975-2016		2000-2016		N/A
	(1)	(2)	(3)	(4)	(5)	(6)
$\Delta \log \widehat{hp}_{i,t-1}$	0.410*** (0.108)	0.392*** (0.107)	0.383*** (0.107)	0.135 (0.124)		0.292** (0.120)
$\Delta \log \widehat{inc}_{i,t-1}$	-0.159 (0.253)	-0.143 (0.251)		-0.0509 (0.251)		0.0871 (0.291)
$\mathcal{I}_{i,t}^{inc} \Delta \log \widehat{hp}_{i,t-1}$		0.804*** (0.285)	0.818*** (0.284)	0.670*** (0.108)	0.687*** (0.102)	
$\mathcal{I}_{i,t}^{hp} \Delta \log \widehat{inc}_{i,t-1}$		0.415** (0.204)	0.406** (0.205)	0.419*** (0.109)	0.425*** (0.107)	
$\Delta \log \widehat{hp}_{i,t-1} \Delta \log \widehat{inc}_{i,t-1}$						4.998** (2.129)
Observations	23896	23896	23896	23896	23896	23896
Adjusted $R^2$	0.843	0.844	0.844	0.845	0.845	0.844

*Note:* County and state-year fixed effects are always included. The observations are weighted by the county population in a given year. Standard errors are clustered at the county level, and reported in parentheses. \*\*\*, \*\*, and \* indicate statistical significance at 1 pct., 5 pct., and 10 pct. confidence levels.

I arrive at the parsimonious specification 5 after sequentially having restricted the most insignificant term out and reestimated the model. Here, the house price elasticity is 0.69 if incomes are high, and the income elasticity is 0.43 if house prices are high. Lastly, in specification 6, I add a continuous interaction term. If positive house price and income growth amplify each other, then this might also show up as a continuous interaction, something that I find to be the case.

The LTV and DTI constraints tie the borrowing ability of homeowners to the *levels* of their housing wealth and incomes. Nevertheless, if homeowners must fulfill such constraints, then we should also expect that low *growth rates* of house prices (incomes) eventually lead homeowners to become LTV (DTI) constrained. If this is true and the growth rate of incomes (house prices) was low in the previous year, then the house price (income) elasticity should likely be lower than if the growth rate was high. I now test this prediction by letting  $\mathcal{I}_{i,t}^{hp}$  and  $\mathcal{I}_{i,t}^{inc}$  denote *growth* indicators for house prices and personal incomes in county  $i$  in year  $t$ . The indicators concretely take the value "1" if the growth rate of their input variable was above a certain threshold in the previous year, and the value "0" if it fell below:

$$\mathcal{I}_{i,t}^{hp} \equiv \begin{cases} 0 & \text{if } \Delta \log hp_{i,t-1} \leq \kappa_{hp} \\ 1 & \text{else,} \end{cases} \quad \mathcal{I}_{i,t}^{inc} \equiv \begin{cases} 0 & \text{if } \Delta \log inc_{i,t-1} \leq \kappa_{inc} \\ 1 & \text{else,} \end{cases} \quad (20)$$



**Table 5:** DETERMINANTS OF CREDIT ORIGINATION: GROWTH RATE SHIFTERS (2008-2016)

	$\Delta \log b_t$					
	(1)	(2)	(3)	(4)	(5)	(6)
$\Delta \widehat{\log hp}_{i,t-1}$	0.410*** (0.108)	0.0443 (0.139)		0.116 (0.141)	0.309*** (0.113)	0.0116 (0.136)
$\Delta \widehat{\log inc}_{i,t-1}$	-0.159 (0.253)	-0.0824 (0.278)		-0.0339 (0.270)	-0.202 (0.260)	-0.136 (0.291)
$\mathcal{I}_{i,t}^{inc} \Delta \widehat{\log hp}_{i,t-1}$		0.437** (0.171)	0.451*** (0.149)	0.470*** (0.169)		0.447*** (0.168)
$\mathcal{I}_{i,t}^{hp} \Delta \widehat{\log inc}_{i,t-1}$		0.423*** (0.117)	0.423*** (0.114)		0.460*** (0.113)	0.462*** (0.173)
$\mathcal{I}_{i,t}^{inc}$						0.00870* (0.00523)
$\mathcal{I}_{i,t}^{hp}$						-0.00257 (0.00808)
Observations	23896	23896	23896	23896	23896	23896
Adjusted $R^2$	0.843	0.844	0.844	0.844	0.844	0.844

*Note:* County and state-year fixed effects are always included. The observations are weighted by the county population in a given year. Standard errors are clustered at the county level, and reported in parentheses. \*\*\*, \*\*, and \* indicate statistical significance at 1 pct., 5 pct., and 10 pct. confidence levels.

where  $\kappa_{hp} \in \mathbb{R}$  and  $\kappa_{inc} \in \mathbb{R}$  measure the growth thresholds. Under this specification, the growth indicators partition the house price and income elasticities based on the growth rates of incomes and house prices in the previous year. It is not *a priori* obvious what value the growth thresholds should take, i.e., what defines "low" growth rates of house prices and incomes. I therefore allow the data to choose the thresholds by simulating these in the following way. First, I divide the observations of house price and income growth rates, respectively, into ten percentiles, thus obtaining nine quantiles as potential thresholds for each variable. I then estimate (18) under (20), tentatively trying each of the  $9 \cdot 9 = 81$  possible quantile pair combinations. As the final threshold, I choose the quantile pair that minimizes the root mean square error of the regression. This combination is  $(\kappa_{hp}, \kappa_{inc}) = (0.0269, 0.0131)$ , which is the 60 pct. house price growth quantile and the 20 pct. income growth quantile.

Table 5 reports the ordinary least squares estimates of the second-stage regression in (18) under (20), with  $(\kappa_{hp}, \kappa_{inc}) = (0.0269, 0.0131)$ . I again obtain the parsimonious specification 3 by sequentially restricting insignificant terms out and reestimating the model. According to this specification, the house price elasticity is only positive if the income growth was above 1.3 pct. in the previous year, and the income elasticity is only positive if the house price growth was above 2.7 pct. in the previous year. Thus, only house price

growth conditional on high income growth and income growth conditional on high house price growth increase loan origination. In specifications 4-5, I sequentially test these results on state-dependent elasticities. The results continue to hold. After introducing *either* a conditional house price elasticity *or* a conditional income elasticity, the corresponding unconditional elasticity is insignificant. Furthermore, the newly introduced conditional elasticity is significant with a point estimate similar to the ones in specifications 2-3. Lastly, in specification 6, I check that the statistical significance of the conditional elasticities is not singularly driven by the growth indicators,  $\mathcal{I}_{i,t}^{inc}$  and  $\mathcal{I}_{i,t}^{hp}$ . I find this not to be the case, in that the estimates in front of the growth indicators are largely insignificant, signifying that it is the interactions which drive the significance.

As a final robustness check provided in Appendix G, I use the alternative threshold,  $(\kappa_{hp}, \kappa_{inc}) = (0, 0)$ , where the estimates are partitioned based on whether house prices and incomes fell or grew in the previous year. I find that the house price elasticity is zero if incomes just fell, and that the income elasticity is zero if house prices just fell. All in all, it emerges that the process through which growth in house prices and incomes leads to growth in mortgage credit is not a linear process. Instead, house prices and incomes discretely amplify each others' effect on credit origination, as would be implied by the presence of multiple credit constraints.

## 9 Concluding Remarks

Across the business cycle, banks impose both LTV and DTI limits on loan applicants. However, because house prices and mortgage rates are low in recessions and high in expansions, LTV limits tend to dominate in recessions, and DTI limits tend to dominate in expansions. This – until now, unexplored – systematic discrete switching between credit constraints has fundamental implications for macroeconomics and finance. The switching causes a sizable asymmetric and state-dependent variation in the transmission of housing preference and credit shocks onto real activity. Adverse shocks have larger effects than similarly sized favorable shocks, and a given shock has the largest effects in contractions. The switching also implies that the effective macroprudential tool changes over the business cycle. As a consequence, LTV policies should focus on supporting borrowing in contractions, and DTI policies should focus on constraining borrowing in expansions.

Looking ahead, numerous avenues for future research remain within the macro-housing literature. From an empirical micro perspective, existing studies on the housing net worth, household credit, and firm credit channels mainly consider separate variation in determinants of credit, such as house prices or banks' balance sheets. Future avenues include both how multiple determinants interact within one channel and how the three channels themselves interact. From a time series perspective, a better understanding of the nonlinear transmission of house price shocks remains. For instance, a local projection instrumental variable approach would address concerns about both the functional form of the response

and endogeneity of house prices. From a macro-theory perspective, a large number of models deliver different predictions for how the housing boom-bust cycle affects real activity; e.g., via credit supply constraints ([Justiniano et al., 2018](#)), firm LTV constraints ([Liu et al., 2013](#)), and bank runs ([Gertler and Kiyotaki, 2015](#)), in addition to household LTV and DTI constraints. While some of these predictions may not be mutually exclusive, further work is needed in order to assess the relative importance of each channel. Lastly, from a heterogeneous agents perspective, an avenue includes a better understanding of the implications of heterogeneity in LTV and DTI constrained individuals, related to, e.g., life-cycle variation in credit restrictions or heterogeneous effects of house price and income drops on housing demand and labor supply or the choice to default.

## A Appendix: Evidence on the DTI Limits of Banks

Table A.1 reports the DTI limits that the ten largest U.S. retail banks specify on their websites. All banks that issue mortgage loans require loan applicants to fulfill a DTI requirement contingent on obtaining the loan. The banks either set front-end limits of 28 pct. or back-end limits of 36 pct.<sup>1</sup>

**Table A.1:** DTI LIMITS OF THE TEN LARGEST U.S. RETAIL BANKS

Rank	Name	Domestic Assets (million \$)	DTI Limit	
			Front-end	Back-end
1	JPMorgan Chase Bank	1,676,806	28 pct.	36 pct.
2	Wells Fargo Bank	1,662,311	–	36 pct.
3	Bank of America	1,661,832	–	36 pct.
4	Citibank	821,805	–	36 pct.
5	U.S. Bank	442,844	28 pct.	–
6	PNC Bank	364,084	28 pct.	36 pct.
7	TD Bank	294,830	28 pct.	36 pct.
8	Capital One	289,808	–	–
9	Branch Banking and Trust Company	214,817	28 pct.	–
10	SunTrust Bank	199,970	28 pct.	36 pct.

*Note:* No DTI limits are available from Capital One, since this bank stopped issuing mortgage loans in 2017. All websites were accessed on September 23, 2018. The banks are ranked by the size of their domestic assets as of March 31, 2018, see [Federal Reserve Statistical Release \(2018\)](#).

### Documentation

The following quotes describe the DTI limits that the ten largest U.S. retail banks place on loan applicants contingent on obtaining a loan. No quote is available from Capital One, since this bank stopped issuing mortgage loans in 2017. All websites were accessed on September 23, 2018.

#### JPMorgan Chase Bank

*"Some lending institutions sometimes ascribe to a "28/36" guideline in assessing appropriate debt loads for individuals, meaning housing costs should not exceed 28 percent of gross monthly income, and back end costs should be limited to an additional 8 points for a total of 36 percent."*

Website: [chase.com/news/121115-amount-of-debt](https://www.chase.com/news/121115-amount-of-debt)

<sup>1</sup>The front-end limit only includes debt services on mortgage loans. The back-end limit also includes debt services on other kinds of recurring debt, such as credit card debt, car loans, and student debt.

## **Wells Fargo Bank**

*"Calculating your debt-to-income ratio  
(Rule of thumb: At or below 36%)"*

*"Is your ratio above 36%?"*

*There are loan programs that allow for higher debt-to-income ratios. Consult with a home mortgage consultant to discuss your options. You can also try to reduce your existing monthly debt by paying off one or more obligations. And you may want to think about consolidating existing loan balances at a lower interest rate and payment."*

Website: [wellsfargo.com/mortgage/learning/calculate-ratios/](https://wellsfargo.com/mortgage/learning/calculate-ratios/)

## **Bank of America**

*"Why is my debt-to-income ratio important?"*

*Banks and other lenders study how much debt their customers can take on before those customers are likely to start having financial difficulties, and they use this knowledge to set lending amounts. While the preferred maximum DTI varies from lender to lender, it's often around 36 percent."*

*"How to lower your debt-to-income ratio"*

*If your debt-to-income ratio is close to or higher than 36 percent, you may want to take steps to reduce it."*

Website: [bettermoneyhabits.bankofamerica.com/en/credit/what-is-debt-to-income-ratio](https://bettermoneyhabits.bankofamerica.com/en/credit/what-is-debt-to-income-ratio)

## **Citibank**

*"Your debt-to-income (DTI) ratio is the percentage of your monthly gross income that goes toward paying debts. The lower your DTI ratio, the more likely you are to qualify for a mortgage. Lenders include your monthly debt expenses and future mortgage payments when they consider your DTI."*

*"The preferred DTI ratio is generally around 36%. You can reduce your DTI ratio by limiting your credit card usage and paying down your existing debt."*

Website: [online.citi.com/US/JRS/portal/template.do?ID=mortgage\\_what\\_affects\\_my\\_rates](https://online.citi.com/US/JRS/portal/template.do?ID=mortgage_what_affects_my_rates)

## **U.S. Bank**

*"A standard rule for lenders is that your monthly housing payment (principal, interest, taxes and insurance) should not take up more than 28 percent of your income."*

*"Mortgage payments should not exceed more than 28% of your income before taxes (a standard rule for lenders)"*

Website: [usbank.com/home-loans/mortgage/first-time-home-buyers/how-much-house-can-i-afford.html](https://usbank.com/home-loans/mortgage/first-time-home-buyers/how-much-house-can-i-afford.html)

## **PNC Bank**

*"Know How Much You Can Afford*

*Depending on the amount you have saved for a down payment, your mortgage payment should typically be no more than 28% of your monthly income, and your total debt should be no more than 36%, although debt ratios have some flexibility, depending on mortgage type you choose."*

Website: <https://www.pnc.com/en/personal-banking/borrowing/home-lending/understanding-home-lending-center/home-buyers-basics.html>

*"Start by assessing your income. Then consider liabilities like student loans, credit card balances and auto loans. Ideally, the amount of your monthly debt payments, including your proposed mortgage payment, should be equal to or less than 36% of your gross monthly income."*

Website: <https://www.pnc.com/en/personal-banking/borrowing/home-lending/understanding-home-lending-center/learn-mortgage.html>

## **TD Bank**

*"Monthly housing payment (PITI)*

*This is your total principal, interest, taxes and insurance (PITI) payment per month. This includes your principal, interest, real estate taxes, hazard insurance, association dues or fees and principal mortgage insurance (PMI). Maximum monthly payment (PITI) is calculated by taking the lower of these two calculations:*

- 1. Monthly Income X 28% = monthly PITI*
- 2. Monthly Income X 36% - Other loan payments = monthly PITI*

*Maximum principal and interest (PI)*

*This is your maximum monthly principal and interest payment. It is calculated by subtracting your monthly taxes and insurance from your monthly PITI payment. This calculator uses your maximum PI payment to determine the mortgage amount that you could qualify for."*

Website: <https://tdbank.mortgagewebcenter.com/Resources/Resources/MortgageMax>

## Branch Banking and Trust Company

*"Gross annual income*

*Providing this enables us to estimate how much you will be able to borrow assuming a 28% debt-to-income ratio. Include the total of your gross annual wages and other income that can be used to qualify for this home equity loan or line of credit."*

Website: <https://www.bbt.com/iwov-resources/calculators/BBLoanLine.html>

## SunTrust Bank

*"28. The maximum percentage of your gross monthly income that should go to housing expenses, including your mortgage, taxes and insurance."*

Website: <https://www.suntrust.com/content/dam/suntrust/us/en/resource-center/documents/2018/avoid-these-common-budget-mistakes.pdf>

*Your DTI ratio is all of your monthly debt payments divided by your gross monthly income (the amount earned before taxes and other deductions). It's typically an important part of the home buying process since some lenders require your debt (including your new potential mortgage payments) to make up less than 36% percent of your income.*

Website: <https://www.suntrust.com/resource-center/homeownership/article/ways-to-manage-your-debt-and-still-buy-a-home>

## B Appendix: Dynamic Equilibrium Conditions

### Patient Household

The patient household maximizes its utility function,

$$\mathbb{E}_0 \left\{ \sum_{t=0}^{\infty} \beta^t s_{I,t} \left[ \chi_C \log(c_t - \eta_C c_{t-1}) + \omega_H s_{H,t} \chi_H \log(h_t - \eta_H h_{t-1}) - \frac{s_{L,t}}{1+\varphi} l_t^{1+\varphi} \right] \right\}, \quad (\text{B.1})$$

subject to a budget constraint,

$$\begin{aligned} c_t + q_t(h_t - h_{t-1}) + \frac{1+r_{t-1}}{1+\pi_t} b_{t-1} + k_t + \frac{\iota}{2} \left( \frac{k_t}{k_{t-1}} - 1 \right)^2 k_{t-1} \\ = w_t l_t + \text{div}_t + b_t + (r_{K,t} + 1 - \delta_K) k_{t-1}, \end{aligned} \quad (\text{B.2})$$

where  $\chi_C \equiv \frac{1-\eta_C}{1-\beta\eta_C}$  and  $\chi_H \equiv \frac{1-\eta_H}{1-\beta\eta_H}$ .

The marginal utilities of goods consumption ( $u_{c,t}$ ) and housing services ( $u_{h,t}$ ) are

$$\begin{aligned} u_{c,t} &\equiv \frac{1-\eta_C}{1-\beta\eta_C} \left[ \frac{s_{I,t}}{c_t - \eta_C c_{t-1}} - \beta\eta_C \frac{s_{I,t+1}}{c_{t+1} - \eta_C c_t} \right], \\ u_{h,t} &\equiv \omega_H \frac{1-\eta_H}{1-\beta\eta_H} \left[ \frac{s_{I,t} s_{H,t}}{h_t - \eta_H h_{t-1}} - \beta\eta_H \frac{s_{I,t+1} s_{H,t+1}}{h_{t+1} - \eta_H h_t} \right]. \end{aligned}$$

The patient household maximizes its utility function with respect to housing, labor supply, net borrowing, and nonresidential capital. The resulting first-order conditions are

$$u_{c,t} q_t = u_{h,t} + \beta \mathbb{E}_t \{ u_{c,t+1} q_{t+1} \}, \quad (\text{B.3})$$

$$u_{c,t} w_t = s_{I,t} s_{L,t} l_t^\varphi, \quad (\text{B.4})$$

$$u_{c,t} = \beta \mathbb{E}_t \left\{ u_{c,t+1} \frac{1+r_t}{1+\pi_{t+1}} \right\}, \quad (\text{B.5})$$

$$u_{c,t} \left[ 1 + \iota \left( \frac{k_t}{k_{t-1}} - 1 \right) \right] = \beta \mathbb{E}_t \left\{ u_{c,t+1} \left[ r_{K,t+1} + 1 - \delta_K + \frac{\iota}{2} \left( \frac{k_{t+1}^2}{k_t^2} - 1 \right) \right] \right\}. \quad (\text{B.6})$$



## Impatient Household

The impatient household maximizes its utility function,

$$\mathbb{E}_0 \left\{ \sum_{t=0}^{\infty} \beta^t s_{I,t} \left[ \chi'_C \log(c'_t - \eta_C c'_{t-1}) + \omega_H s_{H,t} \chi'_H \log(h'_t - \eta_H h'_{t-1}) - \frac{s_{L,t}}{1+\varphi} l_t^{1+\varphi} \right] \right\}, \quad (\text{B.7})$$

subject to a budget constraint,

$$c'_t + q_t(h'_t - h'_{t-1}) + \frac{1+r_{t-1}}{1+\pi_t} b'_{t-1} = w'_t l'_t + b'_t, \quad (\text{B.8})$$

and to two occasionally binding credit constraints,

$$b'_t \leq (1-\rho) \frac{b'_{t-1}}{1+\pi_t} + \rho \xi_{LTV,SC,t} s_{LTV,t} \mathbb{E}_t \{ (1+\pi_{t+1}) q_{t+1} h'_t \}, \quad (\text{B.9})$$

$$b'_t \leq (1-\rho) \frac{b'_{t-1}}{1+\pi_t} + \rho \xi_{DTI,SC,t} s_{DTI,t} \mathbb{E}_t \left\{ \frac{(1+\pi_{t+1}) w'_{t+1} l'_t}{\sigma + r_t} \right\}, \quad (\text{B.10})$$

where  $\chi'_C \equiv \frac{1-\eta_C}{1-\beta'\eta_C}$  and  $\chi'_H \equiv \frac{1-\eta_H}{1-\beta'\eta_H}$ .

I solve the utility maximization problem through the method of Lagrange multipliers. The associated Lagrange function before substitution of (B.8) is

$$\mathbb{E}_0 \left\{ \sum_{t=0}^{\infty} \beta^t s_{I,t} \left[ \chi'_C \log(c'_t - \eta_C c'_{t-1}) + \omega_H s_{H,t} \chi'_H \log(h'_t - \eta_H h'_{t-1}) - \frac{s_{L,t}}{1+\varphi} l_t^{1+\varphi} \right. \right. \\ \left. \left. + \lambda_{LTV,t} \left[ (1-\rho) \frac{b'_{t-1}}{1+\pi_t} + \rho \xi_{LTV,SC,t} s_{LTV,t} \mathbb{E}_t \{ (1+\pi_{t+1}) q_{t+1} h'_t \} - b'_t \right] \right. \right. \\ \left. \left. + \lambda_{DTI,t} \left[ (1-\rho) \frac{b'_{t-1}}{1+\pi_t} + \rho \xi_{DTI,SC,t} s_{DTI,t} \mathbb{E}_t \left\{ \frac{(1+\pi_{t+1}) w'_{t+1} l'_t}{\sigma + r_t} \right\} - b'_t \right] \right] \right\},$$

where  $\lambda_{LTV,t}$  denotes the multiplier on (B.9), and  $\lambda_{DTI,t}$  denotes the multiplier on (B.10).

The marginal utilities of goods consumption ( $u'_{c,t}$ ) and housing services ( $u'_{h,t}$ ) are

$$u'_{c,t} \equiv \frac{1-\eta_C}{1-\beta'\eta_C} \left[ \frac{s_{I,t}}{c'_t - \eta_C c'_{t-1}} - \beta' \eta_C \frac{s_{I,t+1}}{c'_{t+1} - \eta_C c'_t} \right], \\ u'_{h,t} \equiv \omega_H \frac{1-\eta_H}{1-\beta'\eta_H} \left[ \frac{s_{I,t} s_{H,t}}{h'_t - \eta_H h'_{t-1}} - \beta' \eta_H \frac{s_{I,t+1} s_{H,t+1}}{h'_{t+1} - \eta_H h'_t} \right].$$

The impatient household maximizes its utility function with respect to housing, labor supply, and net borrowing. The resulting first-order conditions are

$$u'_{c,t}q_t = u'_{h,t} + \beta' \mathbb{E}_t \{ u'_{c,t+1} q_{t+1} \} + s_{I,t} \lambda_{LTV,t} \rho \xi_{LTV} s_{C,t} s_{LTV,t} \mathbb{E}_t \{ (1 + \pi_{t+1}) q_{t+1} \}, \quad (\text{B.11})$$

$$u'_{c,t} w'_t + s_{I,t} \lambda_{DTI,t} \rho \xi_{DTI} s_{C,t} s_{DTI,t} \mathbb{E}_t \left\{ \frac{(1 + \pi_{t+1}) w'_{t+1}}{\sigma + r_t} \right\} = s_{I,t} s_{L,t} l'^{\varphi}, \quad (\text{B.12})$$

$$\begin{aligned} u'_{c,t} + \beta' (1 - \rho) \mathbb{E}_t \left\{ s_{I,t+1} \frac{\lambda_{LTV,t+1} + \lambda_{DTI,t+1}}{1 + \pi_{t+1}} \right\} \\ = \beta' \mathbb{E}_t \left\{ u'_{c,t+1} \frac{1 + r_t}{1 + \pi_{t+1}} \right\} + s_{I,t} (\lambda_{LTV,t} + \lambda_{DTI,t}). \end{aligned} \quad (\text{B.13})$$

### Restatement of the First-Order Condition w.r.t. Net Borrowing

The first-order condition of the impatient household with respect to net borrowing can be restated through recursive substitution in the following way. The first-order conditions for period  $t$  and period  $t + 1$  are

$$\begin{aligned} u'_{c,t} = \beta' \mathbb{E}_t \left\{ u'_{c,t+1} \frac{1 + r_t}{1 + \pi_{t+1}} \right\} + s_{I,t} (\lambda_{LTV,t} + \lambda_{DTI,t}) \\ - \beta' (1 - \rho) \mathbb{E}_t \left\{ s_{I,t+1} \frac{\lambda_{LTV,t+1} + \lambda_{DTI,t+1}}{1 + \pi_{t+1}} \right\}, \end{aligned} \quad (\text{B.14})$$

$$\begin{aligned} u'_{c,t+1} = \beta' \mathbb{E}_{t+1} \left\{ u'_{c,t+2} \frac{1 + r_{t+1}}{1 + \pi_{t+2}} \right\} + s_{I,t+1} (\lambda_{LTV,t+1} + \lambda_{DTI,t+1}) \\ - \beta' (1 - \rho) \mathbb{E}_{t+1} \left\{ s_{I,t+2} \frac{\lambda_{LTV,t+2} + \lambda_{DTI,t+2}}{1 + \pi_{t+2}} \right\}. \end{aligned} \quad (\text{B.15})$$

Substituting (B.15) into (B.14) gives

$$\begin{aligned} u'_{c,t} = \beta'^2 \mathbb{E}_t \left\{ u'_{c,t+2} \frac{1 + r_{t+1}}{1 + \pi_{t+2}} \frac{1 + r_t}{1 + \pi_{t+1}} \right\} \\ + \beta' \mathbb{E}_t \left\{ s_{I,t+1} (\lambda_{LTV,t+1} + \lambda_{DTI,t+1}) \frac{1 + r_t}{1 + \pi_{t+1}} \right\} \\ - \beta'^2 (1 - \rho) \mathbb{E}_t \left\{ s_{I,t+2} \frac{\lambda_{LTV,t+2} + \lambda_{DTI,t+2}}{1 + \pi_{t+2}} \frac{1 + r_t}{1 + \pi_{t+1}} \right\} \\ + s_{I,t} (\lambda_{LTV,t} + \lambda_{DTI,t}) - \beta' (1 - \rho) \mathbb{E}_t \left\{ s_{I,t+1} \frac{\lambda_{LTV,t+1} + \lambda_{DTI,t+1}}{1 + \pi_{t+1}} \right\}. \end{aligned} \quad (\text{B.16})$$

The first-order condition for period  $t + 2$  is

$$\begin{aligned} u'_{c,t+2} = \beta' \mathbb{E}_{t+2} \left\{ u'_{c,t+3} \frac{1 + r_{t+2}}{1 + \pi_{t+3}} \right\} + s_{I,t+2} (\lambda_{LTV,t+2} + \lambda_{DTI,t+2}) \\ - \beta' (1 - \rho) \mathbb{E}_{t+2} \left\{ s_{I,t+3} \frac{\lambda_{LTV,t+3} + \lambda_{DTI,t+3}}{1 + \pi_{t+3}} \right\}. \end{aligned} \quad (\text{B.17})$$

Substituting (B.17) into (B.16) gives

$$\begin{aligned}
u'_{c,t} = & \beta'^3 \mathbb{E}_t \left\{ u'_{c,t+3} \frac{1+r_{t+2}}{1+\pi_{t+3}} \frac{1+r_{t+1}}{1+\pi_{t+2}} \frac{1+r_t}{1+\pi_{t+1}} \right\} \\
& + \beta'^2 \mathbb{E}_t \left\{ s_{I,t+2} (\lambda_{LTV,t+2} + \lambda_{DTI,t+2}) \frac{1+r_{t+1}}{1+\pi_{t+2}} \frac{1+r_t}{1+\pi_{t+1}} \right\} \\
& \quad - \beta'^3 (1-\rho) \mathbb{E}_t \left\{ s_{I,t+3} \frac{\lambda_{LTV,t+3} + \lambda_{DTI,t+3}}{1+\pi_{t+3}} \frac{1+r_{t+1}}{1+\pi_{t+2}} \frac{1+r_t}{1+\pi_{t+1}} \right\} \\
& + \beta' \mathbb{E}_t \left\{ s_{I,t+1} (\lambda_{LTV,t+1} + \lambda_{DTI,t+1}) \frac{1+r_t}{1+\pi_{t+1}} \right\} \\
& \quad - \beta'^2 (1-\rho) \mathbb{E}_t \left\{ s_{I,t+2} \frac{\lambda_{LTV,t+2} + \lambda_{DTI,t+2}}{1+\pi_{t+2}} \frac{1+r_t}{1+\pi_{t+1}} \right\} \\
& + s_{I,t} (\lambda_{LTV,t} + \lambda_{DTI,t}) - \beta' (1-\rho) \mathbb{E}_t \left\{ s_{I,t+1} \frac{\lambda_{LTV,t+1} + \lambda_{DTI,t+1}}{1+\pi_{t+1}} \right\}.
\end{aligned} \tag{B.18}$$

This expression can be rewritten as

$$\begin{aligned}
u'_{c,t} = & \beta'^3 \mathbb{E}_t \left\{ u'_{c,t+3} \prod_{j=0}^{3-1} \frac{r_{t+j}}{1+\pi_{t+j+1}} \right\} \\
& + \sum_{i=1}^{3-1} \beta'^i \mathbb{E}_t \left\{ s_{I,t+i} (\lambda_{LTV,t+i} + \lambda_{DTI,t+i}) \prod_{j=0}^{i-1} \frac{r_{t+j}}{1+\pi_{t+j+1}} \right\} \\
& \quad - \sum_{i=1}^{3-1} \beta'^{i+1} (1-\rho) \mathbb{E}_t \left\{ s_{I,t+i+1} \frac{\lambda_{LTV,t+i+1} + \lambda_{DTI,t+i+1}}{1+\pi_{t+i+1}} \prod_{j=0}^{i-1} \frac{r_{t+j}}{1+\pi_{t+j+1}} \right\} \\
& + s_{I,t} (\lambda_{LTV,t} + \lambda_{DTI,t}) - \beta' (1-\rho) \mathbb{E}_t \left\{ s_{I,t+1} \frac{\lambda_{LTV,t+1} + \lambda_{DTI,t+1}}{1+\pi_{t+1}} \right\}.
\end{aligned} \tag{B.19}$$

It now emerges that (B.19) can be generalized  $v$  periods ahead, as

$$\begin{aligned}
u'_{c,t} = & \beta'^v \mathbb{E}_t \left\{ u'_{c,t+v} \prod_{j=0}^{v-1} \frac{r_{t+j}}{1+\pi_{t+j+1}} \right\} \\
& + \sum_{i=1}^{v-1} \beta'^i \mathbb{E}_t \left\{ s_{I,t+i} (\lambda_{LTV,t+i} + \lambda_{DTI,t+i}) \prod_{j=0}^{i-1} \frac{r_{t+j}}{1+\pi_{t+j+1}} \right\} \\
& \quad - \sum_{i=1}^{v-1} \beta'^{i+1} (1-\rho) \mathbb{E}_t \left\{ s_{I,t+i+1} \frac{\lambda_{LTV,t+i+1} + \lambda_{DTI,t+i+1}}{1+\pi_{t+i+1}} \prod_{j=0}^{i-1} \frac{r_{t+j}}{1+\pi_{t+j+1}} \right\} \\
& + s_{I,t} (\lambda_{LTV,t} + \lambda_{DTI,t}) - \beta' (1-\rho) \mathbb{E}_t \left\{ s_{I,t+1} \frac{\lambda_{LTV,t+1} + \lambda_{DTI,t+1}}{1+\pi_{t+1}} \right\},
\end{aligned} \tag{B.20}$$

for  $v \in \{v \in \mathbb{Z} | v > 1\}$ .

## Derivation of the DTI Constraint

A closed-form solution for the net present value of the perpetual income stream, which the patient household obtains the right to under default of the impatient household, can be derived in the following way:

$$\begin{aligned}
S_t &= \mathbb{E}_t \left\{ \frac{(1 + \pi_{t+1})w'_{t+1}l''_t}{1 + r_t} + (1 - \sigma) \frac{(1 + \pi_{t+1})w'_{t+1}l''_t}{(1 + r_t)^2} + (1 - \sigma)^2 \frac{(1 + \pi_{t+1})w'_{t+1}l''_t}{(1 + r_t)^3} + \dots \right\} \\
&= \mathbb{E}_t \left\{ \frac{(1 + \pi_{t+1})w'_{t+1}l''_t}{1 + r_t} \left[ 1 + \frac{1 - \sigma}{1 + r_t} + \left( \frac{1 - \sigma}{1 + r_t} \right)^2 + \dots \right] \right\} \\
&= \mathbb{E}_t \left\{ \frac{(1 + \pi_{t+1})w'_{t+1}l''_t}{1 + r_t} \frac{1}{1 - \frac{1 - \sigma}{1 + r_t}} \right\} \\
&= \mathbb{E}_t \left\{ \frac{(1 + \pi_{t+1})w'_{t+1}l''_t}{\sigma + r_t} \right\}, \tag{B.21}
\end{aligned}$$

where the third line appears from applying the sum formula for a converging infinite geometric series. The series converges if  $\frac{1 - \sigma}{1 + r_t} < 1$ , which is realistically the case.

## Intermediate Firm

The intermediate firm maximizes its profits,

$$\frac{Y_t}{M_{P,t}} - w_t l_t - w'_t l'_t - r_{K,t} k_{t-1}, \quad (\text{B.22})$$

subject to the goods production technology,

$$Y_t = k_{t-1}^\mu (s_{Y,t} l_t^\alpha l'_t{}^{1-\alpha})^{1-\mu}. \quad (\text{B.23})$$

The intermediate firm maximizes its profits with respect to nonresidential capital, employment from the patient household, and employment from the impatient household. The resulting first-order conditions are

$$\mu \frac{Y_t}{M_{P,t} k_{t-1}} = r_{K,t}, \quad (\text{B.24})$$

$$(1 - \mu) \alpha \frac{Y_t}{M_{P,t} l_t} = w_t, \quad (\text{B.25})$$

$$(1 - \mu)(1 - \alpha) \frac{Y_t}{M_{P,t} l'_t} = w'_t. \quad (\text{B.26})$$

## Household Constraints and Market-Clearing Conditions

The goods market clearing condition is

$$c_t + c'_t + k_t - (1 - \delta_K) k_{t-1} + \frac{\iota}{2} \left( \frac{k_t}{k_{t-1}} - 1 \right)^2 k_{t-1} = Y_t. \quad (\text{B.27})$$

The housing market clearing condition is

$$h_t + h'_t = H. \quad (\text{B.28})$$

The loan market clearing condition is

$$b_t = -b'_t. \quad (\text{B.29})$$

## C Appendix: Steady-State Computation

This appendix documents the derivation of the steady-state solution of the model. An exact numerical solution can be reached by combining the resulting relations as it is done in the steady-state code.

### Marginal Utility and Inflation

The marginal utilities of goods consumption are

$$\begin{aligned} u_c &= \frac{1 - \eta_C}{1 - \beta\eta_C} \left[ \frac{1}{c - \eta_C c} - \beta \frac{\eta_C}{c - \eta_C c} \right] & u'_c &= \frac{1 - \eta_C}{1 - \beta'\eta_C} \left[ \frac{1}{c' - \eta_C c'} - \beta' \frac{\eta_C}{c' - \eta_C c'} \right] \\ &= \frac{1 - \eta_C}{1 - \beta\eta_C} \frac{1 - \beta\eta_C}{1 - \eta_C} \frac{1}{c} & &= \frac{1 - \eta_C}{1 - \beta'\eta_C} \frac{1 - \beta'\eta_C}{1 - \eta_C} \frac{1}{c'} \\ &= \frac{1}{c}, & &= \frac{1}{c'}. \end{aligned}$$

The marginal utilities of housing services are

$$\begin{aligned} u_h &= \omega_H \frac{1 - \eta_H}{1 - \beta\eta_H} \left[ \frac{1}{h - \eta_H h} - \beta \frac{\eta_H}{h - \eta_H h} \right] & u'_h &= \omega_H \frac{1 - \eta_H}{1 - \beta'\eta_H} \left[ \frac{1}{h' - \eta_H h'} - \beta' \frac{\eta_H}{h' - \eta_H h'} \right] \\ &= \omega_H \frac{1 - \eta_H}{1 - \beta\eta_H} \frac{1 - \beta\eta_H}{1 - \eta_H} \frac{1}{h} & &= \omega_H \frac{1 - \eta_H}{1 - \beta'\eta_H} \frac{1 - \beta'\eta_H}{1 - \eta_H} \frac{1}{h'} \\ &= \frac{\omega_H}{h}, & &= \frac{\omega_H}{h'}. \end{aligned}$$

Net price inflation is

$$\pi = 0.$$

### First-Order Conditions

The first-order condition of the patient household with respect to net borrowing ( $b_t$ ) is

$$\begin{aligned} u_c &= \beta u_c \frac{1 + r}{1 + \pi} \\ r &= \frac{1}{\beta} - 1. \end{aligned} \tag{C.1}$$

The first-order condition of the patient household with respect to nonresidential capital

$(k_t)$  is

$$\begin{aligned} u_c \left[ 1 + \iota \left( \frac{k}{k} - 1 \right) \right] &= \beta u_c \left[ r_K + 1 - \delta_K - \frac{\iota}{2} \left( \frac{k^2}{k^2} - 1 \right) \right] \\ 1 &= \beta [r_K + 1 - \delta_K] \\ r_K &= r + \delta_K. \end{aligned} \tag{C.2}$$

The first-order condition of the intermediate firm with respect to nonresidential capital  $(k_t)$  is

$$\mu \frac{Y}{M_P k} = r_K. \tag{C.3}$$

Combining (C.2) and (C.3), one gets an expression for the  $\frac{k}{Y}$  ratio:

$$\begin{aligned} \mu \frac{Y}{M_P k} &= \frac{1}{\beta} - (1 - \delta_K) \\ \frac{Y}{k} &= \frac{1 - \beta(1 - \delta_K)}{\beta \mu} M_P \\ \frac{k}{Y} &= \frac{\beta \mu}{1 - \beta(1 - \delta_K)} \frac{1}{M_P} \equiv \aleph_1. \end{aligned} \tag{C.4}$$

The first-order condition of the patient household with respect to housing  $(h_t)$  is

$$\begin{aligned} u_c q &= u_h + \beta u_c q \\ \frac{1}{c} q &= \frac{\omega_H}{h} + \beta \frac{1}{c} q \\ \frac{qh}{c} &= \frac{\omega_H}{1 - \beta} \equiv \aleph_2. \end{aligned} \tag{C.5}$$

The first-order condition of the impatient household with respect to net borrowing  $(b_t)$  is

$$\begin{aligned} u'_c + \beta'(1 - \rho) \frac{\lambda_{LTV} + \lambda_{DTI}}{1 + \pi} &= \beta' u'_c \frac{1 + r_t}{1 + \pi} + \lambda_{LTV} + \lambda_{DTI} \\ \frac{1}{c'} + \beta'(1 - \rho)(\lambda_{LTV} + \lambda_{DTI}) &= \frac{\beta'}{\beta} \frac{1}{c'} + \lambda_{LTV} + \lambda_{DTI} \\ (\lambda_{LTV} + \lambda_{DTI})[\beta'(1 - \rho) - 1] &= \frac{1}{c'} \left[ \frac{\beta'}{\beta} - 1 \right] \\ \lambda_{LTV} + \lambda_{DTI} &= \frac{1 - \frac{\beta'}{\beta}}{c'[1 - \beta'(1 - \rho)]}. \end{aligned}$$

Both credit constraints are, by assumption, binding in the steady state, implying that

$\lambda_{LTV} = \lambda_{DTI}$ . Using this condition, one gets that

$$\lambda_{LTV} = \lambda_{DTI} = \frac{1 - \frac{\beta'}{\beta}}{2c'[1 - \beta'(1 - \rho)]}. \quad (\text{C.6})$$

The first-order condition of the impatient household with respect to housing ( $h'_t$ ) is

$$\begin{aligned} u'_c q &= u'_h + \beta u'_c q + \lambda_{LTV} \rho \xi_{LTV} (1 + \pi) q \\ \frac{1}{c'} q &= \frac{\omega_H}{h'} + \beta' \frac{1}{c'} q + \frac{1 - \frac{\beta'}{\beta}}{2c'[1 - \beta'(1 - \rho)]} \rho \xi_{LTV} q \\ \frac{1}{c'} q h' &= \omega_H + \beta' \frac{1}{c'} q h' + \frac{1 - \frac{\beta'}{\beta}}{2c'[1 - \beta'(1 - \rho)]} \rho \xi_{LTV} q h' \\ \frac{q h'}{c'} &= \frac{\omega_H}{1 - \beta' - \frac{1 - \frac{\beta'}{\beta}}{2[1 - \beta'(1 - \rho)]} \rho \xi_{LTV}} \equiv \aleph_3. \end{aligned} \quad (\text{C.7})$$

The dividends that the retail firms pay to the patient household are

$$div = \left(1 - \frac{1}{M_P}\right) Y. \quad (\text{C.8})$$

## Household Constraints and Market-Clearing Conditions

The LTV constraint is

$$\begin{aligned} b' &= (1 - \rho) \frac{b'}{1 + \pi} + \rho \xi_{LTV} (1 + \pi) q h' \\ b' &= \xi_{LTV} q h'. \end{aligned} \quad (\text{C.9})$$

The DTI constraint is

$$\begin{aligned} b' &= (1 - \rho) \frac{b'}{1 + \pi} + \rho \xi_{DTI} \frac{(1 + \pi) w' l'}{\sigma + r} \\ b' &= \xi_{DTI} \frac{w' l'}{\sigma + r}. \end{aligned} \quad (\text{C.10})$$

The model automatically chooses the LTV limit,

$$\xi_{LTV} = \frac{\xi_{DTI} \frac{w' l'}{\sigma + r}}{q h'}, \quad (\text{C.11})$$

which ensures that both constraints are binding in the steady state, i.e.,

$$\xi_{LTV} q h' = \xi_{DTI} \frac{w' l'}{\sigma + r}.$$



The  $\frac{c}{Y}$  ratio is from the budget constraint of the patient household given by

$$\begin{aligned}
c + q(h - h) + \frac{1+r}{1+\pi}b + k + \frac{\iota}{2}\left(\frac{k}{k} - 1\right)^2 k &= wl + div + b + (r_K + 1 - \delta_K)k \\
c &= wl + div - rb + (r_K - \delta_K)k \\
c &= wl + div + r\xi_{DTI}\frac{w'l'}{\sigma+r} + rk \\
c &= (1-\mu)\alpha\frac{Y}{M_P l}l + \left(1 - \frac{1}{M_P}\right)Y + r\xi_{DTI}\frac{1}{\sigma+r}(1-\mu)(1-\alpha)\frac{Y}{M_P l'}l' + r\aleph_1 Y \\
c &= \left[ (1-\mu)\left(\alpha + r\xi_{DTI}\frac{1}{\sigma+r}(1-\alpha)\right)\frac{1}{M_P} + 1 - \frac{1}{M_P} + r\aleph_1 \right] Y \\
\frac{c}{Y} &= (1-\mu)\left(\alpha + r\xi_{DTI}\frac{1}{\sigma+r}(1-\alpha)\right)\frac{1}{M_P} + 1 - \frac{1}{M_P} + r\aleph_1. \tag{C.12}
\end{aligned}$$

The  $\frac{c'}{Y}$  ratio is from the budget constraint of the impatient household given by

$$\begin{aligned}
c' + q'(h' - h') + \frac{1+r}{1+\pi}b' &= w'l' + b' \\
c' &= w'l' - rb' \\
c' &= w'l' - r\xi_{DTI}\frac{w'l'}{\sigma+r} \\
c' &= w'l'\left(1 - r\xi_{DTI}\frac{1}{\sigma+r}\right) \\
c' &= (1-\mu)(1-\alpha)\frac{Y}{l'}l'\left(1 - r\xi_{DTI}\frac{1}{\sigma+r}\right) \\
\frac{c'}{Y} &= (1-\mu)(1-\alpha)\left(1 - r\xi_{DTI}\frac{1}{\sigma+r}\right). \tag{C.13}
\end{aligned}$$

The real house price is determined by the housing market equilibrium condition, as

$$\begin{aligned}
H &= h + h' \\
q &= \frac{qh + qh'}{H} \\
q &= \frac{\aleph_2 c + \aleph_3 c'}{H}. \tag{C.14}
\end{aligned}$$

## Solutions for Endogenous Variables

The first-order condition of the patient household with respect to labor supply is

$$u_c w = l^\varphi. \tag{C.15}$$

Employment from the patient household is from (C.15) and (B.25) given by

$$\begin{aligned}\frac{1}{u_c}l^\varphi &= (1-\mu)\alpha\frac{Y}{MPl} \\ cl^\varphi &= (1-\mu)\alpha\frac{1}{MPl\frac{1}{Y}} \\ l &= \left[ (1-\mu)\alpha\frac{1}{M_P\frac{c}{Y}} \right]^{\frac{1}{1+\varphi}}.\end{aligned}\tag{C.16}$$

The first-order condition of the impatient household with respect to labor supply is

$$u'_c w' + \lambda_{DTI} \rho \xi_{DTI} (1 + \pi) w' = l'^\varphi.\tag{C.17}$$

Employment from the impatient household is from (C.17) and (B.26) given by

$$\begin{aligned}\frac{1}{u'_c + \lambda_{DTI} \rho \xi_{DTI}} l'^\varphi &= (1-\mu)(1-\alpha)\frac{Y}{M_P l'} \\ \frac{1}{\frac{1}{c'} + \frac{1-\frac{\beta'}{\beta}}{2c'[1-\beta'(1-\rho)]} \rho \xi_{DTI}} l'^\varphi &= (1-\mu)(1-\alpha)\frac{Y}{M_P l'} \\ l' &= \left[ (1-\mu)(1-\alpha)\frac{1}{M_P\frac{c'}{Y}} \left( 1 + \frac{1-\frac{\beta'}{\beta}}{2[1-\beta'(1-\rho)]} \rho \xi_{DTI} \right) \right]^{\frac{1}{1+\varphi}}.\end{aligned}\tag{C.18}$$

Goods production is from the production function given by

$$\begin{aligned}Y &= k^\mu (l^\alpha l'^{1-\alpha})^{1-\mu} \\ Y^{\frac{1}{1-\mu}} &= k^{\frac{\mu}{1-\mu}} l^\alpha l'^{1-\alpha} \\ Y &= \left( \frac{k}{Y} \right)^{\frac{\mu}{1-\mu}} l^\alpha l'^{1-\alpha}.\end{aligned}\tag{C.19}$$

Nonresidential capital is determined by the identity

$$k = \frac{k}{Y} Y.\tag{C.20}$$

The real wages are from (B.25) and (B.26) given by

$$w = (1 - \mu)\alpha \frac{Y}{M_{Pl}}, \quad (\text{C.21})$$

$$w' = (1 - \mu)(1 - \alpha) \frac{Y}{M_{Pl}'}. \quad (\text{C.22})$$

Goods consumption is determined by the identities

$$c = \frac{c}{Y}Y, \quad (\text{C.23})$$

$$c' = \frac{c'}{Y}Y. \quad (\text{C.24})$$

Housing consumption is determined by the identities

$$h = \frac{qh}{c} \frac{c}{q}, \quad (\text{C.25})$$

$$h' = \frac{qh'}{c'} \frac{c'}{q}. \quad (\text{C.26})$$

## D Appendix: Derivation of the DTI Constraint

This appendix demonstrates that the DTI constraint can be derived as an incentive compatibility constraint imposed by the patient household on the impatient household, and that it is a generalization of the natural borrowing limit in [Aiyagari \(1994\)](#). The derivation is separate from the LTV constraint in the sense that the patient household does not internalize the LTV constraint when imposing the DTI constraint.

The impatient household faces the choice of whether or not to default in period  $t + 1$  on the borrowing issued to it in period  $t$ . Suppose that if the impatient household defaults, the patient household obtains the right to repayment through a perpetual income stream commencing at period  $t + 1$ . The payments in the income stream are based on the amount  $\mathbb{E}_t\{(1 + \pi_{t+1})w'_{t+1}l'_t\}$ , and decrease by the amortization rate, reflecting a gradual repayment of the loan. Hence, from a period  $t$  perspective and assuming that the patient household discounts the future by  $r_t$ , the net present value of the perpetual income stream is

$$S_t = \mathbb{E}_t \left\{ \frac{(1 + \pi_{t+1})w'_{t+1}l'_t}{1 + r_t} + (1 - \sigma) \frac{(1 + \pi_{t+1})w'_{t+1}l'_t}{(1 + r_t)^2} + (1 - \sigma)^2 \frac{(1 + \pi_{t+1})w'_{t+1}l'_t}{(1 + r_t)^3} + \dots \right\}.$$

Since the income stream is a converging infinite geometric series ( $\frac{1 - \sigma}{1 + r_t} < 1$  applies), its net present value can be expressed as

$$S_t = \mathbb{E}_t \left\{ \frac{(1 + \pi_{t+1})w'_{t+1}l'_t}{\sigma + r_t} \right\}.$$

Suppose next that it is uncertain whether or not the patient household will receive the income stream to which it is entitled in the case of default. With probability  $\xi_{DTI}$ , the household will receive the full stream, and with complementary probability  $1 - \xi_{DTI}$ , the household will not receive anything. The DTI constraint now arises as an incentive compatibility constraint that the patient household imposes on the impatient household in period  $t$ . Incentive compatibility requires that the value of the loan about to be lent is not greater than the expected income stream in the event of default:

$$\tilde{b}'_t \leq \xi_{DTI} \mathbb{E}_t \left\{ \frac{(1 + \pi_{t+1})w'_{t+1}l'_t}{\sigma + r_t} \right\} + (1 - \xi_{DTI}) \cdot 0.$$

This constraint is a generalization of the natural borrowing limit in [Aiyagari \(1994\)](#). In his seminal paper, he assumed that households may borrow up to the discounted sum of all their future minimum labor incomes, giving him the following constraint:  $\tilde{b}'_t \leq \frac{w^{\min}}{r}$ . Thus, in the phrasing of the present chapter, [Aiyagari \(1994\)](#) assumed that stream payments are certain ( $\xi_{DTI} = 1$ ) and not amortized ( $\sigma = 0$ ).

## E Appendix: Data for Estimation of DSGE Model

The sample covers the U.S. economy in 1975Q1-2017Q4, at a quarterly frequency. The time series are retrieved from the database of the U.S. Federal Reserve Bank of St. Louis. The time series are constructed as described below.

$$\text{Real personal consumption expenditures p.c.: } \frac{\text{PCEC}_t}{\text{PCECTPI}_t \cdot \text{CNP16OV}_t}. \quad (\text{E.1})$$

$$\text{Real home mortgage loan liabilities p.c.: } \frac{\text{HHMSDODNS}_t}{\text{GDPDEF}_t \cdot \text{CNP16OV}_t}. \quad (\text{E.2})$$

$$\text{Real house prices: } \frac{\text{CSUSHPISA}_t}{\text{GDPDEF}_t}. \quad (\text{E.3})$$

$$\text{Real disposable personal income p.c.: } \frac{\text{HNODPI}_t}{\text{GDPDEF}_t \cdot \text{CNP16OV}_t}. \quad (\text{E.4})$$

$$\text{Aggregate weekly hours p.c.: } \frac{\text{AWHI}_t}{\text{CNP16OV}_t}. \quad (\text{E.5})$$

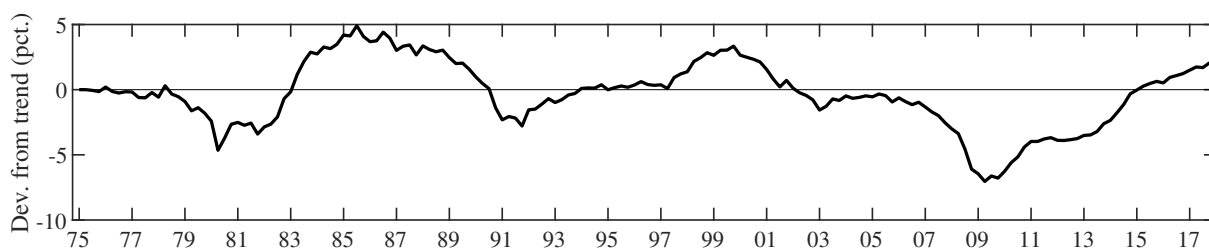
$$\text{Quartered 30-year fixed rate mortgage average: } \frac{\text{MORTGAGE30US}_t}{4 \cdot 100}. \quad (\text{E.6})$$

(E.1)-(E.5) are normalized relative to 1975Q1, then log-transformed, and lastly detrended by series-specific one-sided HP filters, with a smoothing parameter set to 100,000. (E.6) is demeaned. Figure E.1 plots the resulting time series.

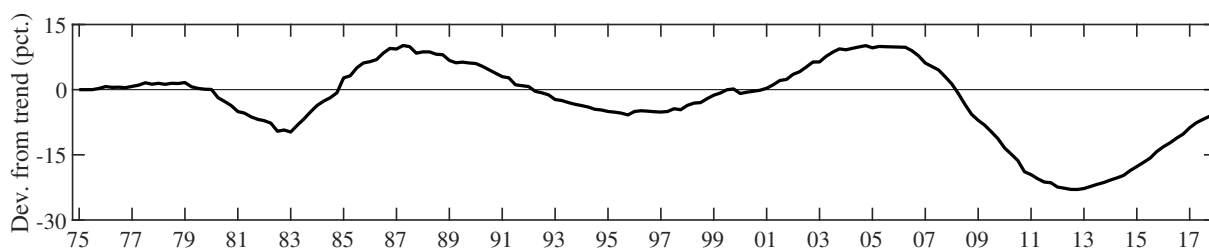
The text codes in (E.1)-(E.6) are the codes applied by the U.S. Federal Reserve Bank of St. Louis. They abbreviate:

- PCEC: Personal Consumption Expenditures (billions of dollars, SA annual rate).
- HHMSDODNS: Households and Nonprofit Organizations; Home Mortgages; Liability, Level (billions of dollars, SA).
- CSUSHPISA: S&P Case-Shiller U.S. National Home Price Index (index, SA).
- HNODPI: Households and Nonprofit Organizations; Disposable Personal Income (billions of dollars, SA annual rate).
- AWHI: Index of Aggregate Weekly Hours: Production and Nonsupervisory Employees: Total Private Industries (index, SA).
- PCECTPI: Personal Consumption Expenditures: Chain-type Price Index (index, SA).
- GDPDEF: Gross Domestic Product: Implicit Price Deflator (index, SA).
- CNP16OV: Civilian Noninstitutional Population (thousands of persons, NSA).
- MORTGAGE30US: 30-Year Fixed Rate Mortgage Average in the United States (percent, NSA).

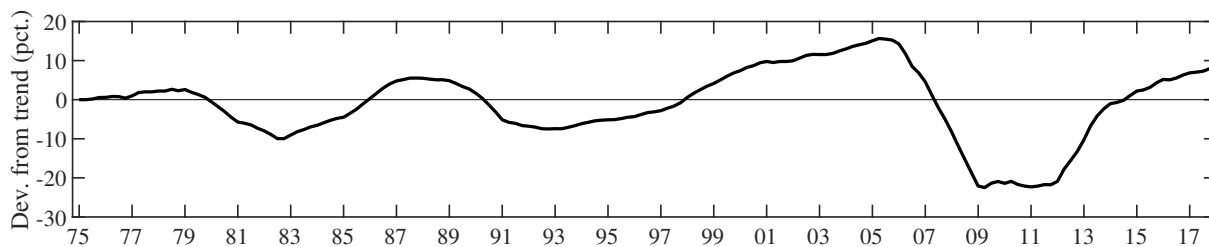
Figure E.1: DATA



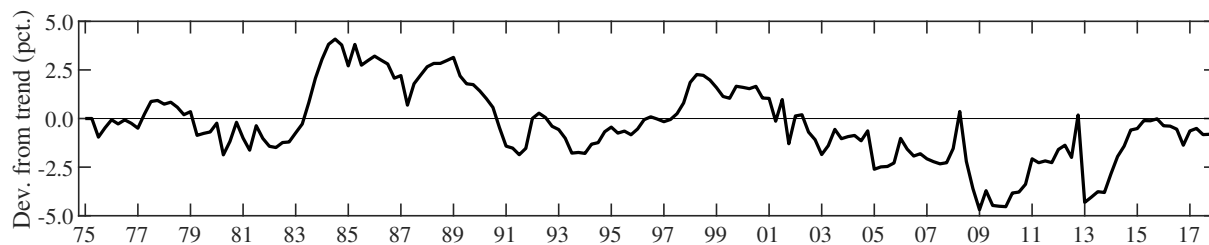
(a) REAL PERSONAL CONSUMPTION EXPENDITURES P.C.



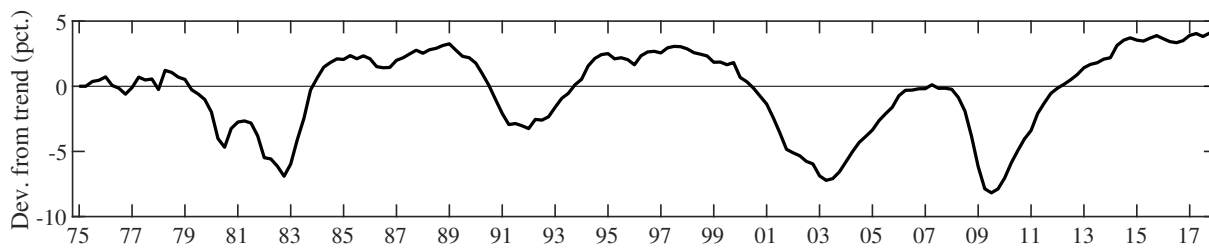
(b) REAL HOME MORTGAGE LOAN LIABILITIES P.C.



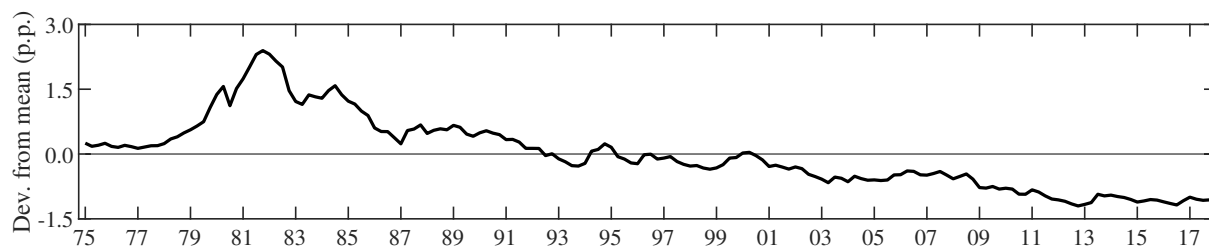
(c) REAL HOUSE PRICES



(d) REAL DISPOSABLE PERSONAL INCOME P.C.



(e) AGGREGATE WEEKLY HOURS P.C.



(f) QUARTERED 30-YEAR FIXED RATE MORTGAGE AVERAGE

## F Appendix: Macroprudential Policy Implications

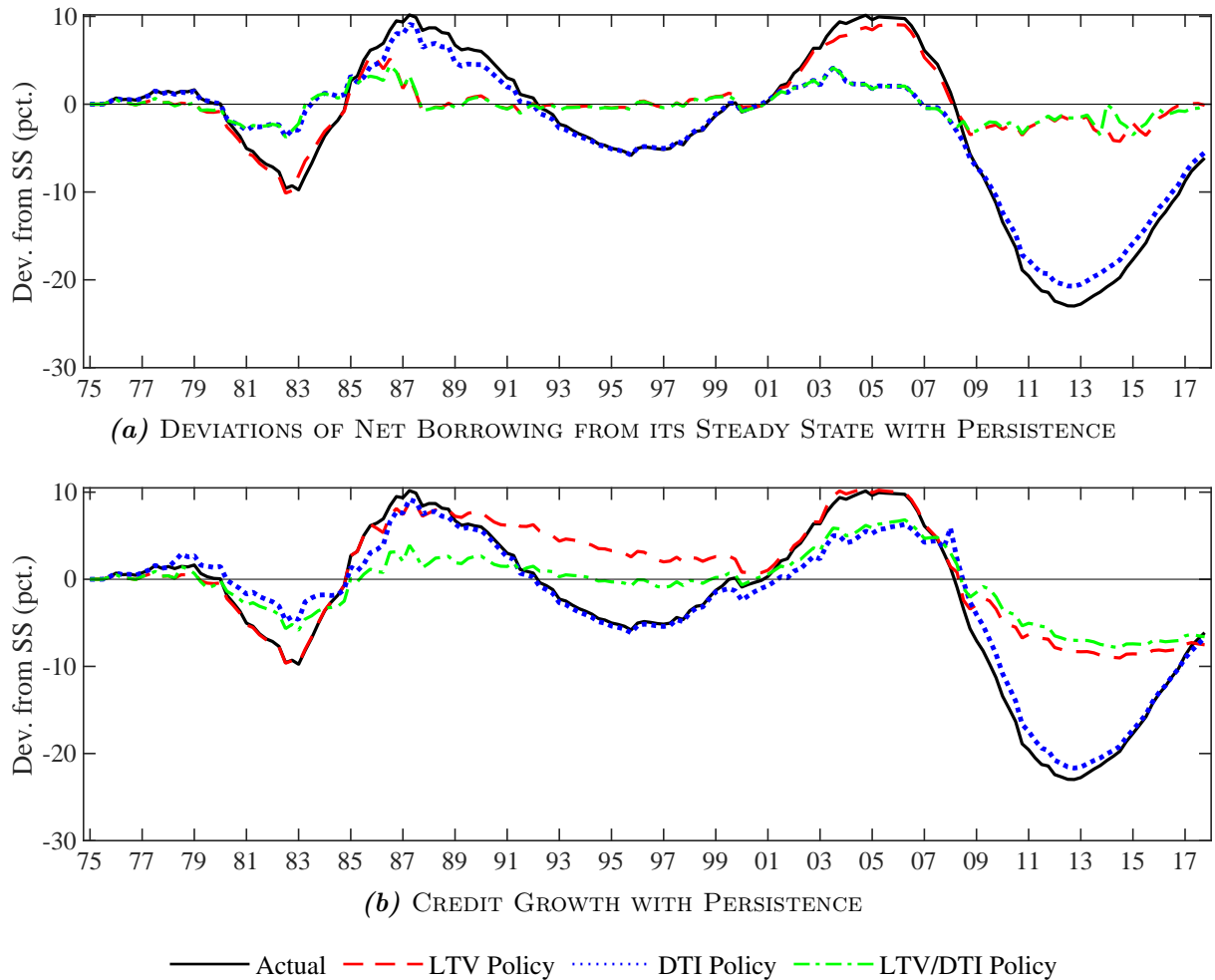
Figure F.1 plots the reaction of borrowing to the estimated sequence of shocks under four different macroprudential regimes conditional on policy rules that are different from the rules in the main text. The rules in Figure F.1a respond negatively with a unit elasticity and some persistence to deviations of borrowing from its steady-state level:

$$\begin{aligned}\log s_{LTV,t} &= 0.75 \cdot \log s_{LTV,t-1} - (\log b'_t - \log b'), \\ \log s_{DTI,t} &= 0.75 \cdot \log s_{DTI,t-1} - (\log b'_t - \log b').\end{aligned}$$

The rules in Figure F.1b respond negatively also with some persistence to the quarterly year-on-year growth in borrowing:

$$\begin{aligned}\log s_{LTV,t} &= 0.75 \cdot \log s_{LTV,t-1} - (\log b'_t - \log b'_{t-4}), \\ \log s_{DTI,t} &= 0.75 \cdot \log s_{DTI,t-1} - (\log b'_t - \log b'_{t-4}).\end{aligned}$$

*Figure F.1: ALTERNATIVE MACROPRUDENTIAL REGIMES: NET BORROWING*



*Note:* The simulations are performed at the baseline posterior mode.

## G Appendix: Evidence on State-Dependent Credit Origination

Table G.1 reports the ordinary least squares estimates of the second-stage regression model under the growth indicator specification with  $(\kappa_{hp}, \kappa_{inc}) = (0, 0)$ .

**Table G.1:** DETERMINANTS OF CREDIT ORIGINATION (2008-2016)

	$\Delta \log b_t$					
	(1)	(2)	(3)	(4)	(5)	(6)
$\Delta \log \widehat{hp}_{i,t-1}$	0.410*** (0.108)	0.0109 (0.161)		0.0415 (0.161)	0.349*** (0.108)	-0.0344 (0.159)
$\Delta \log \widehat{inc}_{i,t-1}$	-0.159 (0.253)	-0.0400 (0.284)		0.0433 (0.280)	-0.240 (0.257)	-0.00201 (0.293)
$\mathcal{I}_{i,t}^{inc} \Delta \log \widehat{hp}_{i,t-1}$		0.501*** (0.176)	0.507*** (0.136)	0.534*** (0.174)		0.518*** (0.173)
$\mathcal{I}_{i,t}^{hp} \Delta \log \widehat{inc}_{i,t-1}$		0.305*** (0.107)	0.303*** (0.108)		0.349*** (0.106)	0.155 (0.169)
$\mathcal{I}_{i,t}^{inc}$						0.00263 (0.00568)
$\mathcal{I}_{i,t}^{hp}$						0.0101 (0.00740)
Observations	23896	23896	23896	23896	23896	23896
Adjusted $R^2$	0.843	0.844	0.844	0.844	0.844	0.844

*Note:* County and state-year fixed effects are always included. The observations are weighted by the county population in a given year. Standard errors are clustered at the county level, and reported in parentheses. \*\*\*, \*\*, and \* indicate statistical significance at 1 pct., 5 pct., and 10 pct. confidence levels.





## Chapter 2

# Not Moving and Not Commuting: Macroeconomic Responses to a Housing Lock-In

*By:* Marcus Mølbak Ingholt

Internal migration correlates positively with house prices and mortgage credit and negatively with wage inflation over the U.S. business cycle. I present a DSGE model in which declining house prices and tight credit conditions impede the relocation propensity of indebted workers, leading them to live farther away from their workplace. In order to avoid paying high commuting premia, firms start hiring workers more locally, which, as the workers gain local market power, raises wages and unemployment. From an estimation of the model, I find that adverse credit shocks were the prime culprits behind the historic decline in migration from 2005 to 2010. Absent this decline, the unemployment rate would have been 0.6 p.p. lower.

*JEL classification:* D58, E24, E32, E44, R23.

*Keywords:* Collateral constraint. Internal migration. Commuting. Wage setting.

# 1 Introduction

Three characteristics of the U.S. business cycle are that internal migration has a positive correlation with house prices and mortgage credit and a negative correlation with wage inflation. This was most evident around the Great Recession, when the cross-county migration rate of homeowners decreased by around one-third, real house prices and mortgage credit fell by 31 pct. and 13 pct., and wage disinflation went missing.<sup>1</sup> The patterns are, however, also present over the longer 1987-2016 timespan, as shown in Figure 1. Here, the migration rate has a 68 pct. correlation with real house price growth, a 62 pct. correlation with real mortgage credit growth, and a  $-25$  pct. correlation with real wage inflation. Lastly, the negative relationship between wage inflation and migration can – as this chapter will demonstrate – be found by estimating a migration-augmented New Keynesian Wage Phillips Curve. Here, migration has a strong and statistically significant negative effect on wage inflation, which improves the explanatory power of the Phillips curve notably.

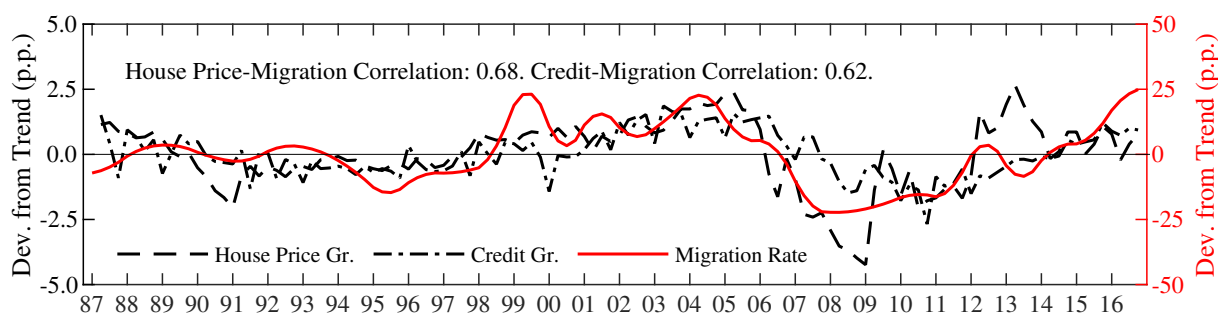
I interpret these business cycle facts in a New Keynesian dynamic stochastic general equilibrium (DSGE) model through two channels: one from the housing market to labor migration and one from labor migration to wage setting. The first channel captures how homeowners become locked in to their current place of residence if rendered technically insolvent by adverse house price and credit shocks. This channel is able to generate the positive empirical relationship between house prices, credit, and migration. The second channel captures how firms, in order to avoid paying high commuting premia, start hiring workers more locally if the workers' relocation propensity falls, which then, as the workers gain local market power, raises the real wage. This channel is able to generate the negative empirical relationship between migration and wages.

The full model incorporates the following dynamics. Unemployment results from workers setting their wages under monopolistic competition. Workers who anticipate unemployment can avoid becoming unemployed by relocating to new areas where they have job offers, but relocating requires indebted workers to refinance their mortgage loans. House price drops render indebted workers technically insolvent, while credit tightenings lower loan-to-value limits. Such adverse disturbances therefore make indebted workers less willing to accept long-distance job offers, as they require the workers to reduce consumption in order to pay back their excess debt. If the relocation propensity of workers falls, the average commuting distance of employed workers starts to increase, since fewer workers are relocating to live near a new workplace. This, *ceteris paribus*, increases the commuting premium that the representative firm compensates the workers with. In order to reduce these commuting costs, the firm increasingly hires locally. As a result, cross-area competition between workers for jobs falls, inducing the workers to target higher wage markups. Lower migration thereby raises the real wage, as in [Bhaskar, Manning, and To \(2002\)](#),

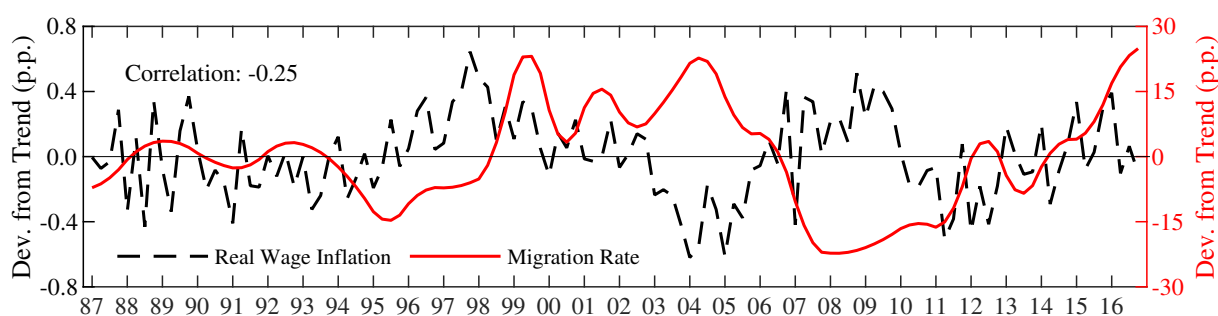
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<sup>1</sup>These changes are calculated over 2006Q4-2009Q4. The puzzle of missing disinflation following the Great Recession has been raised by, e.g., [Hall \(2013\)](#).

Figure 1: HP FILTERED MACROECONOMIC TIME SERIES



(a) REAL HOUSE PRICE AND MORTGAGE CREDIT GROWTH RATES AND THE MIGRATION RATE



(b) REAL WAGE INFLATION AND THE MIGRATION RATE

Note: The migration rate captures cross-county migration of homeowners. The HP smoothing parameter is equal to  $10^5$ , following Shimer (2005) and Sterk (2015).

and increases the geographical wage dispersion, as in Topel (1986), Blanchard and Katz (1992), and Beaudry, Green, and Sand (2014). Furthermore, the economy contracts.

I estimate the model by Bayesian maximum likelihood. This allows me to substantiate the migration-wage channel further. As it turns out, the marginal data density clearly favors the model over an alternative model in which migration does not have an effect on wage setting. Next, using the estimated model, I present a series of results.

The model contributes to an understanding of what determines the internal migration of homeowners. The annual cross-county migration rate of homeowners gradually declined by 0.4 p.p. or 12 pct. from 1987 to 2000 and then, more rapidly, by 1.0 p.p. or 37 pct. from 2005 to 2010. The model predicts the entire decline that occurred around the Great Recession. The decline was caused by a mortgage lock-in of homeowners. Adverse collateral constraint shocks that lowered loan-to-value limits account for 83 pct. of the decline. Adverse housing preference shocks, which drove house prices down, additionally account for 14 pct. of the decline. The decline in migration prior to 2000 is, by contrast, mostly captured by relocation preference shocks. These shocks are highly persistent. This suggests that the decline prior to 2000 had a secular nature, which was unrelated to the cyclical employment motive of the model.

By endogenizing the migration effects on wage setting, the migration-wage channel amplifies the real responses to housing market shocks, in particular, as these shocks largely drive migration. The migration-wage channel thereby sheds light on how the housing

boom-bust cycle affects the economy. This is clearest around the Great Recession, when GDP dropped by 10.0 pct. and unemployment rose by 5.5 p.p. According to the estimation, 0.5 p.p. of the drop in GDP and 0.6 p.p. of the rise in unemployment can be traced to the migration-wage channel. The channel functions as a real wage rigidity that reduces the countercyclicality of real wages, by encouraging workers to target higher wages when migration is low. The model, in this way, offers an explanation of "the missing disinflation" following the Great Recession, exemplified by [Karabarounis \(2014\)](#), who finds that the average wage markup increased by 14 pct. More generally, the migration-wage channel also helps to explain the countercyclicality of wage markups over longer timespans.<sup>2</sup>

The model confirms the [Oswald \(1996\)](#) hypothesis. According to this hypothesis, the natural unemployment rate will be high in economies with high homeownership rates, due to homeowners being less mobile than renters at the labor market. [Oswald \(1996\)](#) originally showed that regions with a 10 p.p. higher homeownership rate have a 2 p.p. higher unemployment rate. In the model, a reduction in migration (stemming from the housing market) increases both the wage and the natural unemployment level.

The results in the chapter advocate policies that increase labor migration over the business cycle and policies, such as countercyclical loan-to-value limits, that can make migration less procyclical. Less procyclical migration will – through the migration-wage channel – reduce the countercyclicality of desired wage markups, and make wages more procyclical, thus moderating the cyclical fluctuations in (un)employment.

The rest of the chapter is structured as follows. Section 2 discusses how the chapter relates to the existing literature. Section 3 provides empirical evidence on the relationship between internal migration and wage setting. Section 4 presents the theoretical model. Section 5 performs the Bayesian estimation of the model. Section 6 examines the drivers of homeowners' migration and the implications of the migration-wage channel. Section 7 contains the concluding remarks.

## 2 Related Literature

The chapter is, to my knowledge, the first to consider the linkage between internal labor migration and commuting in a business cycle environment. A large literature already studies the effects of the housing boom-bust cycle on real activity relying on models with collateral constraints.<sup>3</sup> Within this literature, [Sterk \(2015\)](#) complementarily studies the implications of spatial search and matching, using a collateral constraint which requires homeowners to refinance upon relocating. The present chapter provides new insights into the consequences of this friction. First, in contrast to [Sterk \(2015\)](#), who focuses exclusively on housing preference and technology shocks in a calibrated setting, I distinguish between

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<sup>2</sup>[Karabarounis \(2014\)](#) decomposes the labor wedge into price and wage markups, and shows that the wage markup had a –62 pct. cyclical correlation with GDP per capita during 1964-2011.

<sup>3</sup>See, e.g., [Kiyotaki and Moore \(1997\)](#), [Iacoviello \(2005\)](#), [Iacoviello and Neri \(2010\)](#), [Liu et al. \(2013\)](#), [Justiniano et al. \(2015\)](#), and [Jensen et al. \(2018\)](#).

housing preference, collateral constraint, and nine other shocks in an estimated setting. This difference is crucial, because my estimation ascribes considerably more relevance to collateral constraint and relocation shocks than to housing preference shocks (and none to technology shocks) in driving migration. Second, the channel through which relocations affect the economy differs across the two contributions. As a result, my model is able to capture the negative empirical relationship between migration and wages, again unlike [Sterk \(2015\)](#), who takes wages to be exogenous. The difference in propagation mechanisms is further crucial, since the effects of migration under migration-dependent wage setting may be much larger than under spatial search and matching. With search and matching, the effects of workers becoming geographically immobile only relates to the workers who, at the margin, were discouraged from relocating. Under migration-dependent wage setting, by contrast, the effects may be much larger, because of spill-over on the wages of all workers (including workers not considering relocating) via labor market competition.

Indebted homeowners in the model are forced to refinance their mortgage loans when relocating, which affects their willingness to do so. This requirement can be rationalized either on the basis of recourse loan legislation or, in nonrecourse states, on the basis of long-lasting adverse effects on credit scores of a mortgage default ([FICO, 2018](#)). A vast microeconomic literature finds evidence of a lock-in effect of technical insolvency.<sup>4</sup> Some of the original contributions include [Stein \(1995\)](#) and [Henley \(1998\)](#). [Chan \(2001\)](#) and [Ferreira, Gyourko, and Tracy \(2010\)](#) use pre-recession data, and find that technical insolvency makes homeowners 24 pct. to one-third less mobile. [Ferreira, Gyourko, and Tracy \(2012\)](#) reexamine this conclusion with recession data, and confirm that it continues to hold. [Goetz \(2013\)](#) finds that homeowners who experienced a decline in their homevalues during 2002-2010 were 20-25 pct. less likely to accept new jobs outside their current Metropolitan Statistical Area (MSA). This magnitude is consistent with [Anderson and Mayock \(2014\)](#), who conclude that negative equity reduced household migration by 25 pct. during the crisis. Furthermore, [Monras \(2015\)](#) establish that, across MSAs during 2006-2010, being more severely affected by the crisis had a strong negative effect on in-migration rates, while out-migration rates were unchanged, which indicates that the existing inhabitants were locked in. Finally, [Brown and Matsa \(2016\)](#) find that technical insolvency made homeowners more than 50 pct. less likely to apply for jobs outside their current commuting zone, using data for the financial services industry between May 2008

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<sup>4</sup>Some studies have questioned the size of the lock-in effect on homeowners' migration. For instance, [Molloy, Smith, and Wozniak \(2011\)](#) and [Farber \(2012\)](#) show that the absolute decline in the internal migration rate from 2006 to 2010 was larger for renters than for owners. This, however, does not by itself imply that owners were not locked in. First, as [Molloy et al. \(2011\)](#) also note, the relative decline in the migration rate was larger for owners than for renters. Second, owners and renters are very different demographic groups. Thus, it may be that migration declined for different sets of reasons for them. [Molloy et al. \(2011\)](#) suggest that the decline in migration from 1980-2000 could be caused by two-career households becoming more prevalent, an expansion of telecommuting and flexible work schedules, and a de-specialization of locations in the types of products produced. If these factors predominantly affect renters, e.g., because they are, on average, younger and more newly educated, then an observed decline in the migration of renters should not imply that owners were not locked-in.

and December 2009.

### 3 Empirical Evidence on a Migration-Wage Channel

This section provides empirical evidence on a relationship between internal migration and wage setting. I estimate a reduced-form representation of the standard Galí (2011) New Keynesian Wage Phillips Curve after it has been augmented with a migration term. The reduced-form representation is derived by assuming that the unemployment and migration rates are well represented by covariance-stationary AR(1) processes. The resulting system of equations is

$$\pi_{W,t} = \tilde{\gamma}_W \pi_{P,t-1} + \tilde{\beta} \mathbb{E}_t \{ \pi_{W,t+1} - \tilde{\gamma}_W \pi_{P,t} \} - \tilde{\lambda}_W \tilde{\varphi} u_t + \tilde{\kappa}_M f(m_t) + s_{W,t}, \quad (1)$$

$$u_t = \varsigma_U u_{t-1} + v_{U,t}, \quad (2)$$

$$f(m_t) = \varsigma_M f(m_{t-1}) + v_{M,t}, \quad (3)$$

where  $\tilde{\lambda}_W \equiv \frac{(1-\tilde{\theta}_W)(1-\tilde{\beta}\tilde{\theta}_W)}{\tilde{\theta}_W(1+\tilde{\epsilon}_W\tilde{\varphi})}$  and  $\mathbb{E}\{s_{W,t}\} = \mathbb{E}\{v_{U,t}\} = \mathbb{E}\{v_{M,t}\} = 0$ . Moreover,  $\pi_{W,t}$  denotes net wage inflation,  $\pi_{P,t}$  denotes net price inflation,  $u_t$  denotes the unemployment rate, and  $f(m_t)$  denotes a positive monotone transformation of the migration rate ( $m_t$ ).

The reduced-form New Keynesian Wage Phillips Curve is defined as the solution to the system consisting of (1)-(3), and is derived in Appendix A. The solution is

$$\pi_{W,t} = \tilde{\gamma}_W \pi_{P,t-1} + \sigma_U u_t + \sigma_M f(m_t) + s_{W,t}. \quad (4)$$

The solution implies two cross-equation restrictions:  $\sigma_U = -\frac{\tilde{\lambda}_W \tilde{\varphi}}{1-\tilde{\beta}\varsigma_U}$  and  $\sigma_M = \frac{\tilde{\kappa}_M}{1-\tilde{\beta}\varsigma_M}$ .

The estimation sample is identical to the estimation sample that I use for the Bayesian estimation in Section 5.<sup>5</sup> Nominal wage inflation, price inflation, and the unemployment rate are covariance-stationary at a 5 pct. confidence level. The internal migration rate contains a unit root. I therefore transform this variable in three different ways to obtain covariance-stationarity:  $f(m_t) = m_t - \bar{m}_t$  where  $\bar{m}_t$  is an estimated quadratic trend,  $f(m_t) = \frac{1}{4}\Delta^4 m_t = \frac{1}{4}(m_t - m_{t-4})$ , and  $f(m_t) = \frac{1}{4}\Delta^4 \log m_t = \frac{1}{4}(\log m_t - \log m_{t-4})$ .

Table 1 reports the ordinary least squares estimates of (4). The following sign properties are theory consistent given the reduced-form assumptions that I made above:  $\tilde{\gamma}_W \geq 0$  and  $\tilde{\sigma}_U < 0$ .  $\tilde{\sigma}_U < 0$  always applies at a 1 pct. confidence level. The point estimates of the Calvo wage rigidity parameter ( $\tilde{\theta}_W$ ) range from 0.77 to 0.89, suggesting a substantial wage rigidity, in line with Galí's (2011) results.<sup>6</sup> The point estimates of  $\tilde{\sigma}_M$  are statistically significantly negative at a 1 pct. confidence level with the first transformation and at

<sup>5</sup>(1)-(4) do not contain any constant terms, since their variables have been demeaned.

<sup>6</sup>It is necessary to condition on  $\tilde{\varphi}$  and  $\tilde{\epsilon}_W$ , since the three parameters are not separately identified. Both  $\tilde{\varphi}$  and  $\tilde{\epsilon}_W$  are controversial parameters, so I consider two combinations of them: ( $\tilde{\varphi} = 1.00, \tilde{\epsilon}_W = 17.2$ ) and ( $\tilde{\varphi} = 4.36, \tilde{\epsilon}_W = 5.00$ ). The second combination is identical to the posterior mode in Subsection 5.3. The first combination assumes a low plausible value for  $\tilde{\varphi}$ , with  $\tilde{\epsilon}_W$  being calibrated to be consistent with a steady-state unemployment rate of 6.00 pct., following Galí (2011).

**Table 1:** OLS ESTIMATES OF THE REDUCED-FORM NEW KEYNESIAN WAGE PHILLIPS CURVE

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
$u_t$	-0.086*** (0.012)	-0.082*** (0.014)	-0.113*** (0.006)	-0.084*** (0.013)	-0.082*** (0.013)	-0.109*** (0.007)	-0.080*** (0.014)	-0.080*** (0.014)
$\pi_{P,t-1}$		0.115** (0.056)				0.100** (0.048)	0.087 (0.057)	0.077 (0.056)
$m_t - \bar{m}_t$			-1.067*** (0.268)			-1.052*** (0.250)		
$\frac{1}{4}\Delta^4 m_t$				-2.170* (1.207)			-1.908 (1.176)	
$\frac{1}{4}\Delta^4 \log m_t$					-0.020** (0.008)			-0.018** (0.008)
Adj. $R^2$	0.326	0.336	0.449	0.347	0.366	0.456	0.350	0.368
$\tilde{\theta}_W _{\tilde{\varphi}=1.00}$	0.80*** (0.01)	0.80*** (0.02)	0.77*** (0.01)	0.80*** (0.01)	0.80*** (0.02)	0.77*** (0.01)	0.80*** (0.02)	0.80*** (0.02)
$\tilde{\theta}_W _{\tilde{\varphi}=4.36}$	0.89*** (0.01)	0.89*** (0.01)	0.87*** (0.00)	0.89*** (0.01)	0.89*** (0.01)	0.87*** (0.00)	0.89*** (0.01)	0.89*** (0.01)

*Note:* Time period: 1987Q1-2016Q4. Number of observations: 116. Newey-West standard errors are reported in parentheses. \*\*\*, \*\*, and \* indicate statistical significance at 1 pct., 5 pct., and 10 pct. confidence levels. The estimates of  $\tilde{\theta}_W$  are conditioned on calibrated values of the inverse labor supply elasticity ( $\tilde{\varphi}$ ) and the wage elasticity of labor demand ( $\tilde{\epsilon}_W$ ).

a 5 pct. confidence level with the third transformation. With the second transformation, the point estimates are also negative, albeit only at a borderline significance level. The explanatory power of the regression model increases notably when migration is introduced into it. Introducing migration does not significantly shift the point estimates of the other variables. All in all, the estimates suggest that there is a negative relationship between the relocation propensity of homeowners and wage inflation.

## 4 Model

The model has an infinite time horizon. Time is discrete, and indexed by  $t$ . The economy is populated by two representative households: a patient household and an impatient household. Households consume goods and housing services, supply labor, and relocate for employment purposes. Patient workers are restricted in their decision to relocate by a utility loss, while impatient workers are restricted in their decision to relocate by a utility loss and a refinancing requirement. The time preference heterogeneity implies that the patient household lends funds to the impatient household. Goods and housing are produced by a representative intermediate firm, by combining employment, nonresidential capital, and land. Retail firms and workers unilaterally set prices and nominal wages subject to downward-sloping demand curves. The patient household owns and operates the firms, nonresidential capital, and land. Internal labor migration – through its positive effect on the intermediate firm’s labor substitutability – affects local labor demand and



wage setting. The equilibrium conditions are derived in Appendices B-C.

The model does not have a rental market, since all workers are assumed to be homeowners. While this is a common assumption in the literature (e.g., Sterk, 2015), it may imply that the model overestimates the effect of house price slumps on the propensity to relocate, since renters who have no mortgages should *not* be locked-in. Reversely, however, the model does also not capture spatial search and matching. This may imply that it underestimates the effects of fluctuating labor migration, especially if the effects of spatial matching and migration-dependent wage setting amplify each other.

## 4.1 Patient and Impatient Households

Variables and parameters without (with) a prime refer to the patient (impatient) household. The household types differ with respect to their pure time discount factors,  $\beta \in (0, 1)$  and  $\beta' \in (0, 1)$ , since  $\beta > \beta'$ . The economic size of each household is measured by its wage share:  $\alpha \in (0, 1)$  for the patient household and  $1 - \alpha$  for the impatient household.

Each household consists of a continuum of members, represented by the unit cube and indexed by the triplet  $(i, j, k) \in [0, 1] \times [0, 1] \times [0, 1]$ . The dimension indexed by  $i$  represents the individual disutility from labor supply. The disutility from labor supply of member  $i$  is  $i^\varphi$  if she supplies labor and zero otherwise, where  $\varphi \in \mathbb{R}_+$  measures the elasticity of marginal disutility of supplying labor. The dimension indexed by  $j$  represents the individual disutility from relocating. The disutility from relocating of member  $j$  is  $j^\chi$  if she relocates and zero otherwise, where  $\chi \in \mathbb{R}_+$  measures the elasticity of marginal disutility of relocating. The households choose the labor force participation and migration rates of their members.<sup>7</sup> All labor market participating members supply one unit of time. The dimension indexed by  $k$  represents the geographical specialization of each member. This dimension is elaborated in Subsection 4.3.

The patient and impatient households maximize their utility functions,

$$\mathbb{E}_0 \left\{ \sum_{t=0}^{\infty} \beta^t s_{I,t} \left[ \Xi \log(c_t - \eta c_{t-1}) + \omega_H s_{H,t} \log(h_t) - \frac{s_{L,t}}{1+\varphi} l_t^{1+\varphi} - \frac{\omega_R s_{R,t}}{1+\chi} m_t^{1+\chi} \right] \right\}, \quad (5)$$

$$\mathbb{E}_0 \left\{ \sum_{t=0}^{\infty} \beta'^t s'_{I,t} \left[ \Xi' \log(c'_t - \eta c'_{t-1}) + \omega_H s'_{H,t} \log(h'_t) - \frac{s'_{L,t}}{1+\varphi} l'^{1+\varphi}_t - \frac{\omega_R s'_{R,t}}{1+\chi} m'^{1+\chi}_t \right] \right\}, \quad (6)$$

where  $\Xi \equiv \frac{1-\eta}{1-\beta\eta}$  and  $\Xi' \equiv \frac{1-\eta}{1-\beta'\eta}$ ,<sup>8</sup>  $c_t$  and  $c'_t$  denote goods consumption,  $h_t$  and  $h'_t$  denote housing,  $l_t$  and  $l'_t$  denote labor force participation rates,  $m_t$  and  $m'_t$  denote the average internal migration rates of all workers in a household,<sup>9</sup>  $s_{I,t}$  is an intertemporal preference shock,  $s_{H,t}$  is a housing preference shock,  $s_{L,t}$  is a labor preference shock, and  $s_{R,t}$  is

<sup>7</sup>The heterogeneous disutility of relocating captures heterogeneity in pecuniary and psychological costs across workers. It will always be the workers with the lowest disutility who relocate.

<sup>8</sup> $\Xi$  and  $\Xi'$  ensure that the marginal utilities of goods consumption are  $\frac{1}{c}$  and  $\frac{1}{c'}$  in the steady state.

<sup>9</sup>The disutilities from labor supply and relocation at household levels are computed in the following ways:  $\int_0^1 i^\varphi di = \frac{1}{1+\varphi} l_t^{1+\varphi}$ ,  $\int_0^1 i^\varphi di = \frac{1}{1+\varphi} l'^{1+\varphi}_t$ ,  $\int_0^{m_t} j^\chi dj = \frac{1}{1+\chi} m_t^{1+\chi}$ , and  $\int_0^{m'_t} j^\chi dj = \frac{1}{1+\chi} m'^{1+\chi}_t$ .

a relocation preference shock. Moreover,  $\eta \in (0, 1)$  measures habit formation in goods consumption, while  $\omega_H \in \mathbb{R}_+$  and  $\omega_R \in \mathbb{R}_+$  weight the (dis)utilities of housing services and relocation relative to the utility of goods consumption.<sup>10</sup>

In the beginning of each period, a share of random workers in each household ( $u_{a,t}$  and  $u'_{a,t}$ ) are selected to be unemployed in the current period. I refer to these workers as that they "anticipate unemployment". Out of these shares of workers, a share in each household ( $m_{u,t}$  and  $m'_{u,t}$ ) chooses to avoid unemployment by relocating to new areas where they have job offers. All staying workers who anticipated to be unemployed become unemployed, and all relocating workers become employed. Staying and relocating employed workers earn identical wages. Household wage incomes are thus

$$(1 - u_{a,t})w_t l_t + u_{a,t}m_{u,t}w_t l_t \quad \text{and} \quad (1 - u'_{a,t})w'_t l'_t + u'_{a,t}m'_{u,t}w'_t l'_t, \quad (7)$$

where  $u_{a,t}$  and  $u'_{a,t}$  denote unemployment anticipation rates,  $w_t$  and  $w'_t$  denote *total* real wages, and  $m_{u,t}$  and  $m'_{u,t}$  denote the internal migration rates of the workers who anticipate unemployment. The theoretical models in [Blanchard and Katz \(1992\)](#), [Beaudry et al. \(2014\)](#), and [Sterk \(2015\)](#) also assume that workers relocate for employment purposes.<sup>11</sup>

Utility maximization of the patient household is subject to a budget constraint,

$$\begin{aligned} c_t + q_t h_t + \frac{R_{t-1}}{1 + \pi_{P,t}} b_{t-1} + \frac{k_t}{s_{AK,t}} + \frac{f(z_t)}{s_{AK,t}} k_{t-1} + \frac{g(k_t, k_{t-1})}{s_{AK,t}} k_{t-1} + v_t + p_{X,t} x_t + \alpha s_{G,t} \\ = (1 - u_{a,t})w_t l_t + u_{a,t}m_{u,t}w_t l_t + div_t + (1 - \delta_H)q_t h_{t-1} + b_t \\ + \left( r_{K,t} z_t + \frac{1 - \delta_K}{s_{AK,t}} \right) k_{t-1} + p_{V,t} v_t + (r_{X,t} + p_{X,t})x_{t-1}, \end{aligned} \quad (8)$$

where  $f(z_t) \equiv r_K \left( \frac{1}{2} \frac{\zeta}{1-\zeta} z_t^2 + \left(1 - \frac{\zeta}{1-\zeta}\right) z_t + \frac{1}{2} \frac{\zeta}{1-\zeta} - 1 \right)$  captures capital utilization costs, and  $g(k_t, k_{t-1}) \equiv \frac{\zeta}{2} \left( \frac{k_t}{k_{t-1}} - 1 \right)^2$  captures capital adjustment costs. Moreover,  $q_t$  denotes the real house price,  $R_t$  denotes the nominal gross interest rate,  $\pi_{P,t}$  denotes net price inflation,  $b_t$  denotes net borrowing,  $k_t$  denotes nonresidential capital,  $s_{AK,t}$  is an investment-specific technology shock,  $z_t$  denotes the utilization rate of nonresidential capital,  $r_{K,t}$  denotes the real net rental rate of nonresidential capital,  $r_K$  denotes the steady-state real net rental rate of nonresidential capital,  $v_t$  denotes intermediate housing inputs,  $p_{V,t}$  denotes the real price of intermediate housing inputs,  $x_t$  denotes land,  $p_{X,t}$  denotes the real price of land,  $r_{X,t}$  denotes the real net rental rate of land,  $\alpha s_{G,t}$  is a government spending

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<sup>10</sup>It is not necessary to weight the disutility of labor supply, since its steady-state level only affects the scale of the economy, as in [Justiniano et al. \(2015\)](#). The calibration of  $\omega_R$  ensures that, conditional on the size of the shocks hitting the economy, the internal migration rate is always positive.

<sup>11</sup>The assumption that workers primarily relocate for employment purposes has received empirical support. [Blanchard and Katz \(1992\)](#) show that it is the geographical differences in employment conditions (not wage conditions) which drive labor migration, and that job creation and job migration do not play any particular part in the adjustments of local labor markets. [Beaudry et al. \(2014\)](#) corroborate this by demonstrating that the effects of changes in employment rates on net-migration are three times as large as the effects of changes in wages.

lump-sum tax shock, and  $div_t$  denotes dividends from retail firms. Finally,  $\delta_H \in [0, 1]$  measures the depreciation of residential capital,  $\delta_K \in [0, 1]$  measures the depreciation of nonresidential capital,  $\zeta \in (0, 1)$  measures capital utilization costs, and  $\iota \in \mathbb{R}_+$  measures capital adjustment costs.

Utility maximization of the impatient household is subject to a budget constraint,

$$\begin{aligned} c'_t + q_t h'_t + \frac{R_{t-1}}{1 + \pi_{P,t}} b'_{t-1} + (1 - \alpha) s_{G,t} \\ = (1 - u'_{a,t}) w'_t l'_t + u'_{a,t} m'_{u,t} w'_t l'_t + (1 - \delta_H) q_t h'_{t-1} + b'_t, \end{aligned} \quad (9)$$

and to a collateral constraint,

$$\begin{aligned} b'_t \leq (1 - m'_t) \left( (1 - \rho) \frac{b'_{t-1}}{1 + \pi_{P,t}} + \rho \xi s_{C,t} \mathbb{E}_t \left\{ \frac{(1 + \pi_{P,t+1}) q_{t+1} h'_t}{R_t} \right\} \right) \\ + m'_t \xi s_{C,t} \mathbb{E}_t \left\{ \frac{(1 + \pi_{P,t+1}) q_{t+1} h'_t}{R_t} \right\}, \end{aligned} \quad (10)$$

where  $b'_t$  denotes net borrowing,  $(1 - \alpha) s_{G,t}$  is a government spending lump-sum tax shock, and  $s_{C,t}$  is a collateral constraint shock.  $\rho \in [0, 1]$  measures the share of staying workers who refinance, and  $\xi \in [0, 1]$  measures the steady-state loan-to-value limit on newly issued debt. The assumption  $\beta > \beta'$  implies that (10) always holds with equality around the steady state. Hence, the impatient household is always credit constrained.

The collateral constraint ties the borrowing ability of the relocating share of workers ( $m'_t$ ) to the expected discounted value of their housing wealth. Among the share of workers who do not relocate ( $1 - m'_t$ ), an exogenous share ( $\rho$ ), nonetheless, refinance their mortgage loans, and an exogenous share ( $1 - \rho$ ) roll over their existing mortgages. (10) has the important implication that the relocation choice of the impatient workers is conditioned on the state of the housing market (including the level of outstanding debt).

(10) is a generalization of the collateral constraint in [Sterk \(2015\)](#). He assumes that only relocating homeowners refinance; i.e.,  $\rho = 0$ . I allow for  $\rho > 0$ , since homeowners, in reality, also refinance their mortgage loans without relocating. Thus, assuming  $\rho = 0$  will imply too little correspondence between the collateral value and the actual debt.

## 4.2 Internal Migration

The households choose the internal migration rates of the workers who anticipate unemployment ( $m_{u,t}$  and  $m'_{u,t}$ ) when maximizing utility. However, it is the average migration rates of all workers in the households ( $m_t$  and  $m'_t$ ) that yield disutility and affect borrowing. The average migration rates are

$$\begin{aligned} m_t &\equiv (1 - u_{a,t}) \cdot 0 + u_{a,t} m_{u,t} \\ &= u_{a,t} m_{u,t} \end{aligned} \quad \text{and} \quad \begin{aligned} m'_t &\equiv (1 - u'_{a,t}) \cdot 0 + u'_{a,t} m'_{u,t} \\ &= u'_{a,t} m'_{u,t}. \end{aligned} \quad (11)$$

The households hence choose migration subject to (11). The resulting first-order conditions with respect to migration are

$$u_{c,t}w_t l_t = \omega_{RSR,t} s_{I,t} (u_{a,t} m_{u,t})^\chi,$$

$$u'_{c,t} w'_t l'_t + (1 - \rho) s_{I,t} \lambda_t \left[ \xi_{SC,t} \mathbb{E}_t \left\{ \frac{(1 + \pi_{P,t+1}) q_{t+1} h'_t}{R_t} \right\} - \frac{b'_{t-1}}{1 + \pi_{P,t}} \right] = \omega_{RSR,t} s_{I,t} (u'_{a,t} m'_{u,t})^\chi,$$

where  $u_{c,t}$  and  $u'_{c,t}$  denote the marginal utilities of goods consumption. For the patient household, optimality requires that the marginal utility of consumption made possible by avoiding unemployment via relocating (the left-hand side) is equal to the marginal disutility of relocating (the right-hand side). For the impatient household, in addition to this, the migration choice depends on the difference between the currently loanable amount and the level of outstanding debt. Technical insolvency discourages the workers from relocating, since it requires them to reduce consumption in order to pay back their excess debt. Home equity conversely encourages the workers to relocate, since it gives them an opportunity to take on additional debt and increase consumption.

### 4.3 Firms and the Labor Market

The firm and labor market model is a variant of the model developed in [Erceg et al. \(2000\)](#), most notably expanded with a transformation of goods production into housing and commuting costs.

#### Worker Heterogeneity and Wage Setting

The model captures frictions in the allocation of workers across local labor markets by assuming that the workers are specialized in geography. More precisely, the workers are distributed over a unit continuum,  $k \in [0, 1]$ , of local labor markets. The intermediate firm aggregates employment across these labor markets through two [Dixit and Stiglitz \(1977\)](#) aggregators,

$$n_t = \left( \int_0^1 n_t(k) \frac{e_{W,t}^{-1}}{e_{W,t}} dk \right)^{\frac{e_{W,t}}{e_{W,t}-1}} \quad \text{and} \quad n'_t = \left( \int_0^1 n'_t(k) \frac{e'_{W,t}^{-1}}{e'_{W,t}} dk \right)^{\frac{e'_{W,t}}{e'_{W,t}-1}}, \quad (12)$$

where  $n_t(k)$  and  $n'_t(k)$  denote the employment of patient and impatient workers in area  $k$ , and  $e_{W,t}$  and  $e'_{W,t}$  denote endogenous wage elasticities of local labor demand. Importantly, the wage elasticities measure how willing the intermediate firm is to substitute between workers located in different areas.

The labor market features commuting costs, along the lines of [Becker \(1965\)](#), [Muth \(1969\)](#), [White \(1976\)](#), and [Straszheim \(1984\)](#).<sup>12</sup> The workers receive disutility from the

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<sup>12</sup>[Becker \(1965\)](#) originally predicted that wages should, c.p., increase with the distance of commutes for workers to be indifferent between short- and long-commute jobs. Several studies have found evidence

total time that they are not home – not just the time they spend on the job. This forces the intermediate firm to pecuniarily compensate the workers for their commute. The total real wages that the workers receive (i.e., enter into the workers' budget constraints) consequently have two components:

$$w_t \equiv f(e_{W,t})\tilde{w}_t \quad \text{and} \quad w'_t \equiv f(e'_{W,t})\tilde{w}'_t,$$

where  $f(e_{W,t})$  and  $f(e'_{W,t})$  denote commuting premium functions, and  $\tilde{w}_t$  and  $\tilde{w}'_t$  denote the real wages for workers commuting at a steady-state extent. The commuting premium functions take the following forms:

$$f(e_{W,t}) \equiv mi_t \cdot 0 + (1 - mi_t) \frac{\kappa}{1 + \psi} e_{W,t}^{1+\psi} - \psi e_{W,t} - \Upsilon, \quad (13)$$

$$f(e'_{W,t}) \equiv mi'_t \cdot 0 + (1 - mi'_t) \frac{\kappa}{1 + \psi} e'_{W,t}^{1+\psi} - \psi e'_{W,t} - \Upsilon', \quad (14)$$

where  $\Upsilon \equiv (1 - mi) \frac{\kappa}{1 + \psi} e_W^{1+\psi} - \psi e_W - 1$ ,  $\Upsilon' \equiv (1 - mi') \frac{\kappa}{1 + \psi} e'_W{}^{1+\psi} - \psi e'_W - 1$ , and  $mi_t$  and  $mi'_t$  denote proximity shares. The proximity shares indicate the shares of workers who live in the proximity of their workplace. Finally,  $\kappa \in \mathbb{R}_+$  weights the size of the commuting premium,  $\psi \in \mathbb{R}_+$  measures the marginal cost of additional commuting, and  $\Upsilon$  and  $\Upsilon'$  ensure that  $f(e_W) = f(e'_W) = 1$  in the steady state. The remuneration of the firm to the workers depends on how proximate they live to the firm. For the shares of workers,  $1 - mi_t$  and  $1 - mi'_t$ , who do not live in the proximity of their workplace, the firm is forced to pay a commuting premium that increases convexly in the spatial labor substitution of the firm. This reflects that the farther away the firm wants to hire its workers from, the higher compensation will it be forced to pay.

The laws-of-motion for the proximity shares are

$$mi_t \equiv m_t + (1 - \sigma)mi_{t-1} \quad \text{and} \quad mi'_t \equiv m'_t + (1 - \sigma)mi'_{t-1}, \quad (15)$$

where  $\sigma \in (0, 1)$  measures the job hiring rate after excluding relocation-associated job hires. Around the steady state,  $mi_t \in (0, 1)$  and  $mi'_t \in (0, 1)$  for  $0 < m_t < \sigma$  and  $0 < m'_t < \sigma$ . Workers who relocate in the current period (the shares  $m_t$  and  $m'_t$ ) automatically live in the proximity of their new workplace, since they relocated to get a job at a specific firm establishment. Over time, however, the workers switch establishments without relocating (measured by the job hiring rate  $\sigma$ ), implying that the proximity of their workplace, on average, decays. The workers thus gradually start incurring commuting costs, which the firm remunerates.

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of such positive wage gradients, including [Madden \(1985\)](#), [DiMadi and Peddle \(1986\)](#), [Zax \(1991\)](#), and [Timothy and Wheaton \(2001\)](#) for the U.S. and [Vejlín \(2013\)](#) for Denmark.

## New Keynesian Wage Phillips Curves

The geographical specialization of the workers allows them to set the nominal wage under steady-state commutation at each local labor market  $k$  subject to monopolistic competition. Conditional on the solution to the intermediate firm's labor input maximization problem, the solutions to the workers' wage setting problems yield two hybrid New Keynesian Wage Phillips Curves,

$$\tilde{\pi}_{W,t} = \gamma_W \pi_{P,t-1} + \beta \mathbb{E}_t \{ \tilde{\pi}_{W,t+1} - \gamma_W \pi_{P,t} \} - \lambda_{W,t} (\log M_{W,t} - \log M_{W,t}^D) + s_{W,t}, \quad (16)$$

$$\tilde{\pi}'_{W,t} = \gamma_W \pi_{P,t-1} + \beta \mathbb{E}_t \{ \tilde{\pi}'_{W,t+1} - \gamma_W \pi_{P,t} \} - \lambda'_{W,t} (\log M'_{W,t} - \log M_{W,t}^{D'}) + s_{W,t}, \quad (17)$$

where  $\lambda_{W,t} \equiv \frac{(1-\theta_W)(1-\beta\theta_W)}{\theta_W(1+e_{W,t}\varphi)}$ ,  $\lambda'_{W,t} \equiv \frac{(1-\theta_W)(1-\beta'\theta_W)}{\theta_W(1+e'_{W,t}\varphi)}$ ,  $\tilde{\pi}_{W,t}$  and  $\tilde{\pi}'_{W,t}$  denote nominal wage inflation under steady-state commutation,  $M_{W,t} \equiv \frac{(1-u_t)f(e_{W,t})\tilde{W}_t}{P_t MRS_{nc,t}}$  and  $M'_{W,t} \equiv \frac{(1-u'_t)f(e'_{W,t})\tilde{W}'_t}{P_t MRS'_{nc,t}}$  denote wage markups,  $M_{W,t}^D \equiv \frac{e_{W,t}}{e_{W,t}-1}$  and  $M_{W,t}^{D'} \equiv \frac{e'_{W,t}}{e'_{W,t}-1}$  denote endogenous average desired gross wage markups, and  $s_{W,t}$  is a wage markup shock. Furthermore,  $\gamma_W \in [0, 1)$  measures backward price indexation, and  $\theta_W \in (0, 1)$  measures the Calvo probability of local workers not being able to adjust their wage in a given period.

Interpretation of unemployment and identification of the wage markups are based on the Galí (2011) extension of the Erceg et al. (2000) labor market model. With this extension, unemployment results from the wage being set above its perfectly competitive level by the workers. The wage markups are identified through the unemployment rates:

$$\log M_{W,t} = \varphi u_t \quad \text{and} \quad \log M'_{W,t} = \varphi u'_t. \quad (18)$$

The relations in (18) are derived in Appendix B. The natural unemployment rates are defined as the unemployment rates that prevail in the absence of nominal wage rigidities, thus making it possible for the workers to keep the wage markups at the desired levels. Hence, the wage markups in the steady state are identified by

$$\log M_W = \log M'_W = \varphi u = \varphi u', \quad (19)$$

where  $M_W \equiv \frac{\epsilon_W}{\epsilon_W-1}$  and  $M'_W \equiv \frac{\epsilon'_W}{\epsilon'_W-1}$  denote the average desired gross wage markups in the steady state, and  $u \equiv \log l - \log n$  and  $u' \equiv \log l' - \log n'$  denote the natural unemployment rates in the steady state.

## 4.4 Firms

### Intermediate Firm

The intermediate firm produces intermediate goods and housing under perfect competition. It chooses patient and impatient employment ( $n_t$  and  $n'_t$ ), nonresidential capital ( $k_{t-1}$ ), intermediate housing inputs ( $v_t$ ), land ( $x_t$ ), and labor substitution ( $e_{W,t}$  and  $e'_{W,t}$ )

in order to maximize profits. The profits are given by

$$\frac{Y_t}{M_{P,t}} + q_t I_{H,t} - w_t n_t - w'_t n'_t - r_{K,t} z_t k_{t-1} - p_{V,t} v_t - r_{X,t} x_{t-1}, \quad (20)$$

subject to the available goods production and housing transformation technologies,

$$Y_t = (z_t k_{t-1})^\mu (s_{Y,t} n_t^\alpha n'_t)^{1-\mu}, \quad (21)$$

$$I_{H,t} = v_t^\nu x_{t-1}^{1-\nu}, \quad (22)$$

where  $Y_t$  denotes goods production,  $M_{P,t}$  denotes an average gross price markup over marginal costs set by the retail firms,  $I_{H,t}$  denotes housing production,  $n_t$  and  $n'_t$  denote employment rates, and  $s_{Y,t}$  is a labor-augmenting technology shock.<sup>13</sup>  $\mu \in (0, 1)$  measures the goods production elasticity with respect to nonresidential capital, and  $\nu \in (0, 1)$  measures the housing transformation elasticity with respect to intermediate housing inputs.

The profit maximization is also subject to two laws-of-motion for the total real wages. The law-of-motion for the total real wage of the patient workers is

$$\begin{aligned} w_t &\equiv f(e_{W,t}) \tilde{w}_t \\ &= f(e_{W,t}) [\tilde{w}_{t-1} + \tilde{\pi}_{W,t} - \pi_{P,t}] \\ &= f(e_{W,t}) \left[ \tilde{w}_{t-1} + \gamma_W \pi_{P,t-1} + \beta \mathbb{E}_t \{ \tilde{\pi}_{W,t+1} - \gamma_W \pi_{P,t} \} \right. \\ &\quad \left. - \frac{(1 - \theta_W)(1 - \beta \theta_W)}{\theta_W(1 + e_{W,t} \varphi)} \left( \log M_{W,t} - \log \frac{e_{W,t}}{e_{W,t} - 1} \right) + s_{W,t} - \pi_{P,t} \right]. \end{aligned}$$

A functionally equivalent law-of-motion for the total real wage of the impatient workers applies. Through these laws-of-motion, the intermediate firm can influence the remuneration to the workers by choosing in how wide an area to hire labor. The resulting first-order condition with respect to labor substitution between patient workers is

$$\begin{aligned} &f'(e_{W,t}) [\tilde{w}_{t-1} + \tilde{\pi}_{W,t} - \pi_{P,t}] \\ &= f(e_{W,t}) \frac{(1 - \theta_W)(1 - \beta \theta_W)}{\theta_W(1 + e_{W,t} \varphi)} \left[ \frac{1}{e_{W,t}^2} - \frac{\varphi}{1 + e_{W,t} \varphi} \left( \log M_{W,t} - \frac{1}{e_{W,t}} \right) \right]. \quad (23) \end{aligned}$$

A functionally equivalent first-order condition again applies for the impatient workers. Optimality requires that the marginal cost of a higher commuting premium (the left-hand side) is equal to the marginal saving of a lower real wage for a worker commuting at the steady-state extent (the right-hand side).<sup>14</sup> Thus, the intermediate firm trades-off two forces when deciding on the optimal commutation for its workers. On the one hand, only hiring workers in the firm's own vicinity allows the firm to pay low commuting premia,

<sup>13</sup>Nonresidential capital and labor are not used directly in the housing transformation technology, since they have already been used in the production of intermediate housing inputs.

<sup>14</sup> $e_{W,t} > 1$  and  $e'_{W,t} > 1$  always apply in the estimations and simulations reported in Sections 5-6.

but it will suffer the local workers gaining monopoly power, which they use to target high wage markups. On the other hand, hiring workers farther away allows the firm to reduce the monopoly power of its local workers, by substituting more between different labor markets, but the firm will incur higher commuting costs.

### Retail Firms and Price Setting

Retail firms are distributed over a unit continuum by product specialization. They purchase and assemble intermediate goods into retail firm-specific final goods at no additional cost. The final goods are then sold as goods consumption, nonresidential investments, intermediate housing inputs, and government spending. The specialization allows the firms to operate under monopolistic competition, paying dividends to the patient household:

$$div_t \equiv \left(1 - \frac{1}{M_{P,t}}\right) Y_t. \quad (24)$$

The solution to the retail firms' price setting problem yields a hybrid New Keynesian Price Phillips Curve,

$$\pi_{P,t} = \gamma_P \pi_{P,t-1} + \beta \mathbb{E}_t \{ \pi_{P,t+1} - \gamma_P \pi_{P,t} \} - \lambda_P \left( \log M_{P,t} - \log \frac{\epsilon_P}{\epsilon_P - 1} \right) + s_{P,t}, \quad (25)$$

where  $\lambda_P \equiv \frac{(1-\theta_P)(1-\beta\theta_P)}{\theta_P}$  and  $s_{P,t}$  is a price markup shock. Furthermore,  $\epsilon_P > 1$  measures the price elasticity of retail firm-specific goods demand,  $\gamma_P \in [0, 1)$  measures backward price indexation, and  $\theta_P \in (0, 1)$  measures the Calvo probability of a firm not being able to adjust its price in a given period.

## 4.5 Labor Market Equilibrium

The labor market equilibrium conditions require that total household employment is equal to the sum of employment stemming from workers who anticipate to be employed and workers who anticipate to be unemployed but who become employed by relocating:

$$n_t = (1 - u_{a,t})l_t + u_{a,t}m_{u,t}l_t, \quad (26)$$

$$n'_t = (1 - u'_{a,t})l'_t + u'_{a,t}m'_{u,t}l'_t. \quad (27)$$

The labor market equilibrium conditions determine the unemployment anticipation rates. The equilibrium conditions furthermore determine the unemployment rates as

$$\begin{aligned} u_t &\equiv 1 - \frac{n_t}{l_t} & \text{and} & & u'_t &\equiv 1 - \frac{n'_t}{l'_t} \\ &= (1 - m_{u,t})u_{a,t} & & & &= (1 - m'_{u,t})u'_{a,t}. \end{aligned}$$



Disregarding any equilibrium effects of migration (e.g., via the migration-wage channel), a decline in the migration rates of workers who anticipate unemployment ( $m_{u,t}$  and  $m'_{u,t}$ ) causes a decline in the unemployment anticipation rates ( $u_{a,t}$  and  $u'_{a,t}$ ), leaving unemployment ( $u_t$  and  $u'_t$ ) unchanged.

## 4.6 Monetary Policy

A central bank sets the nominal gross interest rate according to a Taylor-type monetary policy rule,

$$R_t = R_{t-1}^{\tau_R} R^{1-\tau_R} \exp(\pi_{P,t})^{(1-\tau_R)\tau_\pi} \left( \frac{GDP_t}{GDP_{t-1}} \right)^{(1-\tau_R)\tau_{\Delta Y}} \exp(\varepsilon_{M,t}), \quad (28)$$

where  $R$  denotes the steady-state nominal gross interest rate,  $GDP_t$  denotes the gross domestic product,<sup>15</sup> and  $\varepsilon_{M,t}$  is a monetary policy innovation. Moreover,  $\tau_R \in (0, 1)$  measures deterministic interest rate smoothing,  $\tau_P > 1$  measures the policy response to price inflation, and  $\tau_{\Delta Y} \geq 0$  measures the policy response to output growth.<sup>16</sup>

## 4.7 Equilibrium

The model contains a goods market, a housing market, and a loan market, in addition to the two labor markets. The market clearing conditions are

$$c_t + c'_t + \frac{k_t - (1 - \delta_K)k_{t-1}}{s_{AK,t}} + \frac{f(z_t)}{s_{AK,t}}k_{t-1} + \frac{g(k_t, k_{t-1})}{s_{AK,t}}k_{t-1} + v_t + s_{G,t} = Y_t, \quad (29)$$

$$h_t + h'_t - (1 - \delta_H)(h_{t-1} + h'_{t-1}) = I_{H,t}, \quad (30)$$

$$b_t = -b'_t, \quad (31)$$

where  $s_{G,t}$  is a government spending shock. The government finances its spending shocks in each period by lump-sum taxation of the households (cf., (8) and (9)).

## 4.8 Stochastic Processes

All stochastic shocks except the monetary policy innovation follow AR(1) processes. The monetary policy innovation is a single-period innovation, so that any persistence in this policy is captured by interest rate smoothing, as in [Christiano et al. \(2014\)](#). All eleven stochastic innovations are normally independent and identically distributed, with a constant standard deviation.

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<sup>15</sup>The gross domestic product is defined as the sum of value-added from goods production and housing transformation.

<sup>16</sup>I do not model a zero lower bound on the nominal interest rate, even though the estimation sample in Section 5 covers 2009Q1-2015Q4, following [Christiano et al. \(2014\)](#). Any effects of the zero lower bound will thus be captured by the monetary policy innovation.

## 5 Estimation

### 5.1 Data

I solve the model with a first-order perturbation method, and estimate it by Bayesian maximum likelihood. The sample covers the U.S. economy in 1987Q1-2016Q4, at a quarterly frequency. The sample contains the following eleven time series: 1. Real gross domestic product per capita.<sup>17</sup> 2. Real personal consumption expenditures per capita. 3. Real private nonresidential investment per capita. 4. Real home mortgage loan liabilities per capita. 5. Real house prices. 6. Quartered effective federal funds rate. 7. Log-change in GDP price deflator. 8. Log-change in average hourly earnings. 9. Log employment-population ratio. 10. Unemployment rate. 11. Cross-county migration rate of homeowners.<sup>18</sup> The initial date of the sample is restricted by the data on the migration rate, which is not available before 1987. Series 1-5 are normalized relative to 1987Q1, then log-transformed, and lastly detrended by series-specific linear trends. Series 6-11 are demeaned. Data sources are reported in Appendix D.

### 5.2 Calibration and Prior Distribution

A subset of the parameters are calibrated using information complementary to the estimation sample. Table 2 reports the calibrated parameters and information on their calibration. The prior means of the price elasticity of goods demand ( $\epsilon_P = 5$ ) and commuting premium weight ( $\kappa = 0.22$ ) imply that prices and wages are marked up by (for wages, approximately) 25 pct. over the marginal costs and marginal rates of substitution in the steady state, following Galí, Smets, and Wouters (2012).

Table 3 reports the prior distributions of the estimated parameters. The mean elasticity of marginal disutility of relocating ( $\chi = 3$ ) takes the median value in the interval  $[1, 5]$  of utility curvature values mostly used in the literature. The mean elasticity of the marginal disutility of labor supply is set to a value consistent with the calibrated steady-state net wage markup of 25 pct. and the average unemployment rate over the sample (6.00 pct.):  $\varphi = \frac{\log 1.25}{0.0600} \simeq 3.72$ . The mean marginal commuting cost parameter ( $\psi = 1$ ) implies agnosticism about whether the marginal commuting premium should increase convexly or concavely in spatial substitution. The means of the Calvo parameters ( $\theta_P = \theta_W = 0.625$ ) are the median between the values associated with reoptimization every two (0.50) and four (0.75) quarters. The job hiring rate after excluding relocation-associated job hires

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<sup>17</sup>To be consistent with the model, GDP is defined as the sum of personal consumption expenditures, private nonresidential investment, private residential investment, and government consumption expenditures and gross investment.

<sup>18</sup>The cross-county migration rate of homeowners is from the Annual Social and Economic Supplement of the Current Population Survey. It is only available at an annual frequency. I therefore use Denton's (1971) method to quarter and interpolate it to a quarterly frequency, following Liu et al. (2013). The data for, e.g., 1987 covers migration between April 1987 and March 1988. Data is missing for 1994, which necessitates me to interpolate 1994 by an arithmetic average of 1993 and 1995.

**Table 2: CALIBRATED PARAMETERS**

Description		Value	Source or Steady-State Target
Wage share, pt. household	$\alpha$	0.70	Other data, <sup>a</sup> <a href="#">Iacoviello (2005)</a> , <a href="#">Iacoviello and Neri (2010)</a>
Time discount factor, pt. hh.	$\beta$	0.9925	<a href="#">Iacoviello and Neri (2010)</a> , <a href="#">Sterk (2015)</a>
Time discount factor, impt. hh.	$\beta'$	0.97	<a href="#">Iacoviello and Neri (2010)</a> , <a href="#">Sterk (2015)</a>
Housing utility weight	$\omega_H$	0.111	Sample data <sup>b</sup>
Relocation disutility weight	$\omega_R$	$\exp(14.3)$	Internal migration rate: 0.8 pct. <sup>c</sup>
Refinancing share	$\rho$	0.0045	<a href="#">Chang and Nothaft (2007)</a> <sup>d</sup>
Steady-state loan-to-value limit	$\xi$	0.85	<a href="#">Iacoviello and Neri (2010)</a>
Price elasticity of goods demand	$\epsilon_P$	5.00	See text
Commuting premium weight	$\kappa$	0.22	See text
Depreciation rate, res. capital	$\delta_H$	0.01	Standard value
Depreciation rate, nonres. capital	$\delta_K$	0.025	Standard value
Housing transformation elasticity	$\nu$	0.90	<a href="#">Davis and Heathcote (2005)</a> , <a href="#">Iacoviello and Neri (2010)</a>

<sup>a</sup>The model roughly matches the average share of households with loan-to-value ratios below 80 pct. (68 pct.) over 1987-2016, in the Monthly Interest Rate Survey of the U.S. Federal Housing Finance Agency.

<sup>b</sup>The model matches the average ratio of residential investment to the sum of consumption and nonresidential and residential investments (5.2 pct.) over 1987-2016.

<sup>c</sup>The model matches the average cross-county migration rate of homeowners over 2000-2005.

<sup>d</sup>The model matches the average share of prime mortgage originations that relate to the refinancing of staying homeowners (50 pct.) over 1990-2005, according to [Chang and Nothaft \(2007\)](#). The corresponding theoretical concept is:  $\frac{(1-m'_t)\rho}{m'_t}$ .

( $\sigma = 0.10$ ) has a prior mean roughly equal to the average quarterly job hiring rate (11.4 pct.) minus the average cross-county migration rate of homeowners (0.8 pct.).<sup>19</sup>

The prior means of the remaining estimated parameters are identical to the calibrated or prior mean values of the corresponding parameters in [Iacoviello and Neri \(2010\)](#).

### 5.3 Posterior Distribution

Table 3 reports two posterior distributions: One from the baseline model and one from a restricted model where the migration-wage channel is inactive. In the restricted model, the proximity shares in (15) are set to their steady-state values, so that migration does not exercise an effect on wage setting through (13)-(14) or (23). The models are otherwise identical. The log marginal data density is 5,282.43 with the baseline posterior model and 5,279.64 with the restricted posterior model. This difference in marginal data densities implies a posterior odds ratio of 16 to 1 in favor of the baseline model.

The marginal commuting cost parameter ( $\psi = 1.60$ ) implies that the marginal commuting premium increases convexly in spatial substitution. The job hiring rate ( $\sigma = 0.08$ ) is slightly lower than its prior mean. This is not surprising, as it suggests that not all job

<sup>19</sup>The total private job hiring rate is taken from the Job Openings and Labor Turnover Survey of the U.S. Bureau of Labor Statistics and averaged over 2000-2016.

**Table 3:** PRIOR DISTRIBUTION AND POSTERIOR DISTRIBUTIONS

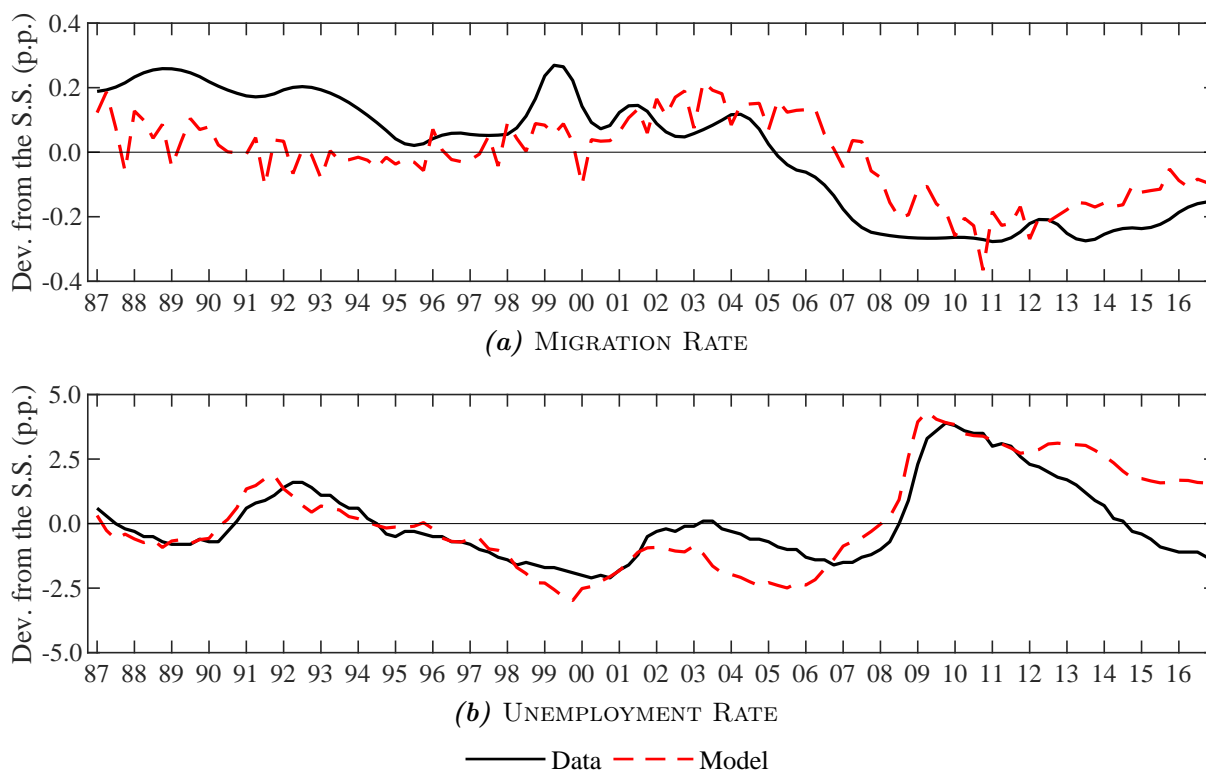
Prior Distribution				Posterior Distributions							
				Baseline Model				Restricted Model			
Type	Mean	S.D.		Mode	Mean	5 pct.	95 pct.	Mode	Mean	5 pct.	95 pct.
<b>Structural Parameters</b>											
$\eta$	B	0.50	0.15	0.46	0.47	0.41	0.54	0.46	0.47	0.41	0.54
$\varphi$	N	3.72	0.50	4.36	4.45	3.74	5.17	4.34	4.43	3.73	5.18
$\chi$	N	3.00	0.15	3.63	3.62	3.41	3.84	3.62	3.61	3.39	3.83
$\zeta$	B	0.50	0.15	0.88	0.86	0.78	0.94	0.88	0.86	0.78	0.94
$\iota$	G	10.0	2.50	25.1	26.7	21.4	32.4	25.1	26.8	21.2	32.1
$\psi$	N	1.00	0.25	1.60	1.60	1.20	2.00	1.60	1.60	1.20	2.00
$\sigma$	B	0.10	0.05	0.08	0.10	0.03	0.17	0.11	0.13	0.05	0.21
$\gamma_P$	B	0.50	0.15	0.09	0.11	0.03	0.19	0.09	0.11	0.04	0.18
$\theta_P$	B	0.625	0.05	0.65	0.63	0.57	0.70	0.64	0.63	0.57	0.69
$\gamma_W$	B	0.50	0.15	0.11	0.13	0.05	0.20	0.10	0.12	0.04	0.19
$\theta_W$	B	0.625	0.05	0.53	0.52	0.45	0.59	0.52	0.51	0.44	0.59
$\tau_R$	B	0.75	0.05	0.76	0.77	0.73	0.80	0.76	0.76	0.73	0.80
$\tau_P$	N	1.50	0.25	1.53	1.69	1.40	1.97	1.53	1.69	1.40	1.97
<b>Autocorrelation of Shock Processes</b>											
IP	B	0.50	0.20	0.95	0.94	0.91	0.96	0.94	0.93	0.91	0.96
HP	B	0.50	0.20	0.97	0.97	0.95	0.98	0.97	0.97	0.95	0.98
RP	B	0.50	0.20	0.92	0.91	0.86	0.96	0.89	0.89	0.84	0.95
CC	B	0.50	0.20	0.80	0.80	0.74	0.87	0.83	0.83	0.77	0.89
GS	B	0.50	0.20	0.99	0.98	0.98	0.99	0.99	0.98	0.98	0.99
AY	B	0.50	0.20	0.99	0.98	0.97	1.00	0.99	0.98	0.97	1.00
AK	B	0.50	0.20	0.97	0.96	0.94	0.99	0.97	0.96	0.94	0.99
PM	B	0.50	0.20	0.90	0.89	0.85	0.94	0.90	0.89	0.85	0.94
LP	B	0.50	0.20	0.99	0.99	0.98	1.00	0.99	0.99	0.98	1.00
WM	B	0.50	0.20	0.94	0.93	0.88	0.98	0.95	0.93	0.89	0.98
<b>Standard Deviations of Innovations</b>											
IP	IG	0.001	0.01	0.013	0.014	0.011	0.017	0.012	0.014	0.010	0.017
HP	IG	0.001	0.01	0.066	0.073	0.055	0.089	0.066	0.073	0.056	0.089
RP	IG	0.001	0.01	0.243	0.246	0.220	0.272	0.243	0.246	0.219	0.273
CC	IG	0.001	0.01	0.463	0.469	0.420	0.519	0.460	0.467	0.416	0.514
MP	IG	0.001	0.01	0.002	0.002	0.001	0.002	0.002	0.002	0.001	0.002
GS	IG	0.001	0.01	0.016	0.016	0.015	0.018	0.016	0.016	0.015	0.018
AY	IG	0.001	0.01	0.007	0.007	0.006	0.008	0.007	0.007	0.006	0.008
AK	IG	0.001	0.01	0.014	0.015	0.012	0.018	0.014	0.015	0.012	0.018
PM	IG	0.001	0.01	0.002	0.002	0.001	0.002	0.002	0.002	0.001	0.003
LP	IG	0.001	0.01	0.014	0.014	0.012	0.016	0.014	0.014	0.012	0.016
WM	IG	0.001	0.01	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001

*Distributions:* N: Normal. B: Beta. G: Gamma. IG: Inverse-Gamma.

*Note:* The model is solved and estimated in `Dynare 4.5.3`. Four parallel Markov chains are generated. Each chain contains 250,000 realizations with the 125,000 initial realizations being discarded. The variance scale factor of the jumping distribution is set to 0.25. The resulting acceptance rates are 36.4, 36.5, 36.5, and 36.6 pct. in the baseline estimation and 34.5, 34.6, 34.7, and 34.6 pct. in the restricted estimation.

turnovers made after relocating result in longer commutes. The standard deviation of the collateral constraint shock is high (46.3 pct.). This is also not surprising, considering that the *refinancing* collateral constraint only restricts the loan-to-value limit on the newly originated share of total debt. In comparison, a more standard single-period collateral

*Figure 2: EMPIRICAL AND THEORETICAL PATHS OF MIGRATION AND UNEMPLOYMENT*



*Note:* The model is parameterized to the mean of the prior distribution. A collateral constraint shock and a labor-augmenting technology shock are simulated such that the paths of GDP and borrowing in the model match the historical paths of GDP and mortgage credit.

constraint restricts the loan-to-value limit on all debts. Since only newly originated debts are affected by the shocks, the shocks must be much larger in order to make the theoretical total debt match the fluctuations in its empirical counterpart.

The remaining posterior distributions are broadly in line with the existing literature (compare with the prior distributions).

## 5.4 Model Validation

### Does the Model Explain Unemployment and Internal Migration?

In this subsection, I evaluate the ability of the model to predict unemployment and internal migration. I parameterize the model to the mean of the prior distribution, and simulate a collateral constraint shock and a labor-augmenting technology shock such that the paths of GDP and borrowing in the model match the historical paths of GDP and mortgage credit. Figure 2 plots the associated theoretical and empirical movements in the unemployment and migration rates. The upper panel of Table 4 reports the standard deviations of the theoretical and empirical series, along with the correlations between them. The lower panel of Table 4 reports the cross-correlations between five variables in the data and model.

The model reasonably precisely predicts the cyclical movements in the unemployment and migration rates. There is a high correlation between the empirical and theoretical

**Table 4:** STANDARD DEVIATIONS AND CORRELATIONS: DATA AND BASELINE MODEL

Standard Deviations and Correlations between Data and Model								
	No Filter				HP Filter			
	Std. Dev.		Corr.		Std. Dev.		Corr.	
	Data	Model			Data	Model		
Migration Rate	0.19	0.12	0.70		0.12	0.14	0.60	
Unemp. Rate	1.48	1.91	0.83		0.20	0.21	0.82	
Cross-Correlations between Variables: No Filter								
	Migration Rate		Unemp. Rate		Mort. Credit Gr.		House Price Gr.	
	Data	Model	Data	Model	Data	Model	Data	Model
Migration Rate	1.00	1.00						
Unemp. Rate	-0.42	-0.82	1.00	1.00				
Mort. Credit Gr.	0.70	1.00	-0.62	-0.83	1.00	1.00		
House Price Gr.	0.31	0.29	-0.35	-0.22	0.46	0.29	1.00	1.00
Cross-Correlations between Variables: HP Filter								
	Migration Rate		Unemp. Rate		Mort. Credit Gr.		House Price Gr.	
	Data	Model	Data	Model	Data	Model	Data	Model
Migration Rate	1.00	1.00						
Unemp. Rate	-0.42	-0.65	1.00	1.00				
Mort. Credit Gr.	0.62	0.99	-0.50	-0.66	1.00	1.00		
House Price Gr.	0.68	0.25	-0.23	-0.22	0.53	0.29	1.00	1.00

*Note:* The model is parameterized to the mean of the prior distribution. A collateral constraint shock and a labor-augmenting technology shock are simulated such that the paths of GDP and borrowing in the model match the historical paths of GDP and mortgage credit. The HP filtered series have been log-transformed and then filtered with a smoothing parameter equal to  $10^5$ , following [Shimer \(2005\)](#) and [Sterk \(2015\)](#).

sequences of the two variables over the sample period (0.70 and 0.83). Furthermore, the volatilities of the empirical and theoretical rates are of similar magnitudes (0.19/0.12 and 1.48/1.91). The model does fail to capture the secular decline in migration from 1987 to 2000. Filtering this deviation out, the standard deviations of the migration rates are almost identical (0.12/0.14).

The cross-correlations between the variables in the model have identical signs and similar magnitudes to the cross-correlations in the data. Migration is positively correlated with house price and credit growth and negatively correlated with unemployment. House price and credit growth are both negatively correlated with unemployment. House price and credit growth are themselves positively correlated.

The fit with respect to the unemployment rate is considerably better than in [Sterk \(2015\)](#). In that paper, the search-and-matching labor market underestimates the volatility of unemployment, leading its standard deviation relative to output to be almost six times

**Table 5:** EMPIRICAL AND THEORETICAL CORRELATIONS WITH THE MIGRATION RATE

	Data	Baseline Estimation	Restricted Estimation
GDP	37	9	2
Nom. Interest Rate	-8	-8	1
Nom. Wage Inf.	-10	-12	0
Employment	27	15	1
Unemployment	-37	-17	4

*Note:* The theoretical correlations are computed at the respective posterior modes. The data have been log-transformed and then HP filtered with a smoothing parameter equal to  $10^5$ , following [Shimer \(2005\)](#) and [Sterk \(2015\)](#).

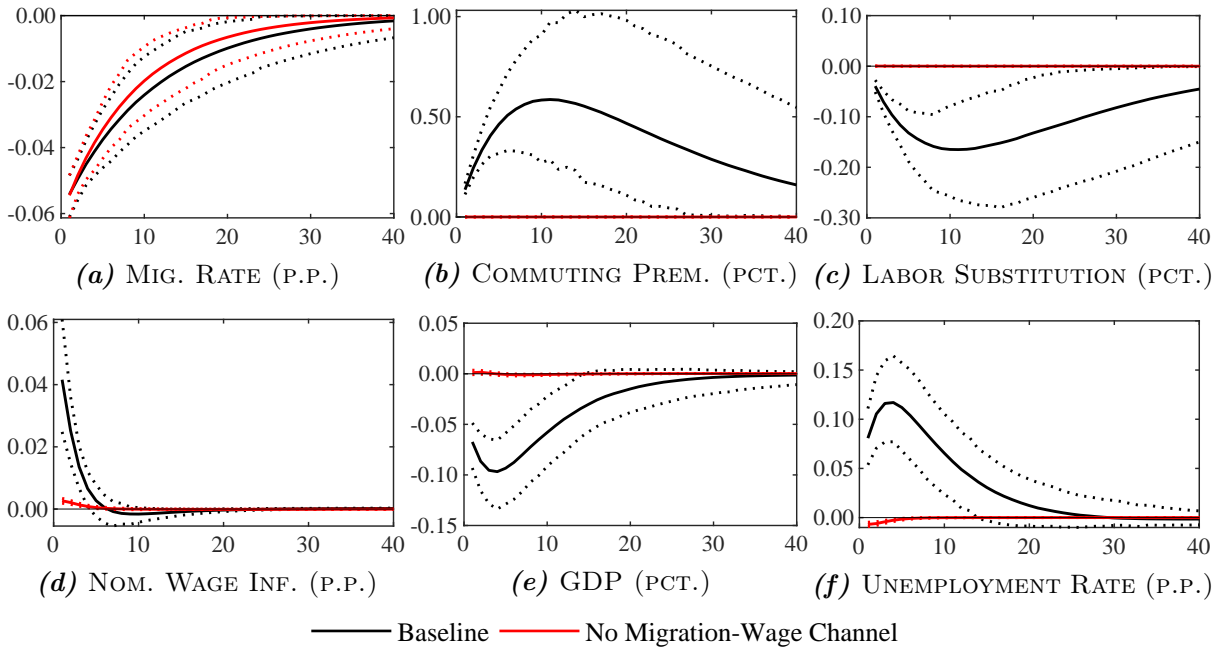
larger in the data (7.28) than in the model (1.22). By contrast, in the current monopolistically competitive model, the standard deviations of the unemployment rate across the model and the data are very close if considering HP filtered series, as in [Sterk \(2015\)](#), and 23 pct. smaller in the data than in the model if considering raw series ( $\frac{1.48}{1.91} - 1$ ).

The reasonably precise fit of the model with respect to migration is not surprising. [Molloy et al. \(2011\)](#) find that homeownership status, employment status, education, and age are the four most important determinants of migration rates across population groups. The predictions of the model are compared to the migration rate of homeowners (consistent with the model assumptions), and the education and age distributions in the U.S. population have likely been roughly time-constant during 1987-2016. This leaves employment status as the only important time-varying determinant of migration. Hence, if the model accurately captures the employment-related migration decisions of homeowners, it should accurately capture the overall migration decisions of homeowners.

### Why Does the Migration-Wage Channel Help the Model Fit the Data?

The marginal data density showed that the model fits the data better with the migration-wage channel than without the channel. In order to understand this better, [Table 5](#) reports the empirical and unconditional theoretical posterior correlations of internal migration with GDP, the nominal interest rate, nominal wage inflation, employment, and unemployment. These variables are all observed in the estimation, and consequently contribute to determining the fit of the model. Without the migration-wage channel, migration is uncorrelated with GDP, the interest rate, wage inflation, and (un)employment. This lack of correlation is at odds with the data. Migration empirically has a positive correlation with GDP and employment and a negative correlation with the interest rate, wage inflation, and unemployment. With the migration wage channel, the model is better able to replicate these characteristics.

**Figure 3: RESPONSES TO A POSITIVE RELOCATION PREFERENCE SHOCK**



*Note:* The figures plot the 5 pct. bound, median, and 95 pct. bound of the posterior impulse responses from the baseline and restricted estimations, following unit standard deviation shocks. Vertical axes measure deviations from the steady state.

## 6 Model Dynamics

I now use the estimated model to further assess the implications of the migration-wage channel. I first discuss how the channel affects the propagation of shocks. I then decompose the historical volatility in internal migration. I lastly examine the role of the migration-wage channel in accounting for the Great Recession.

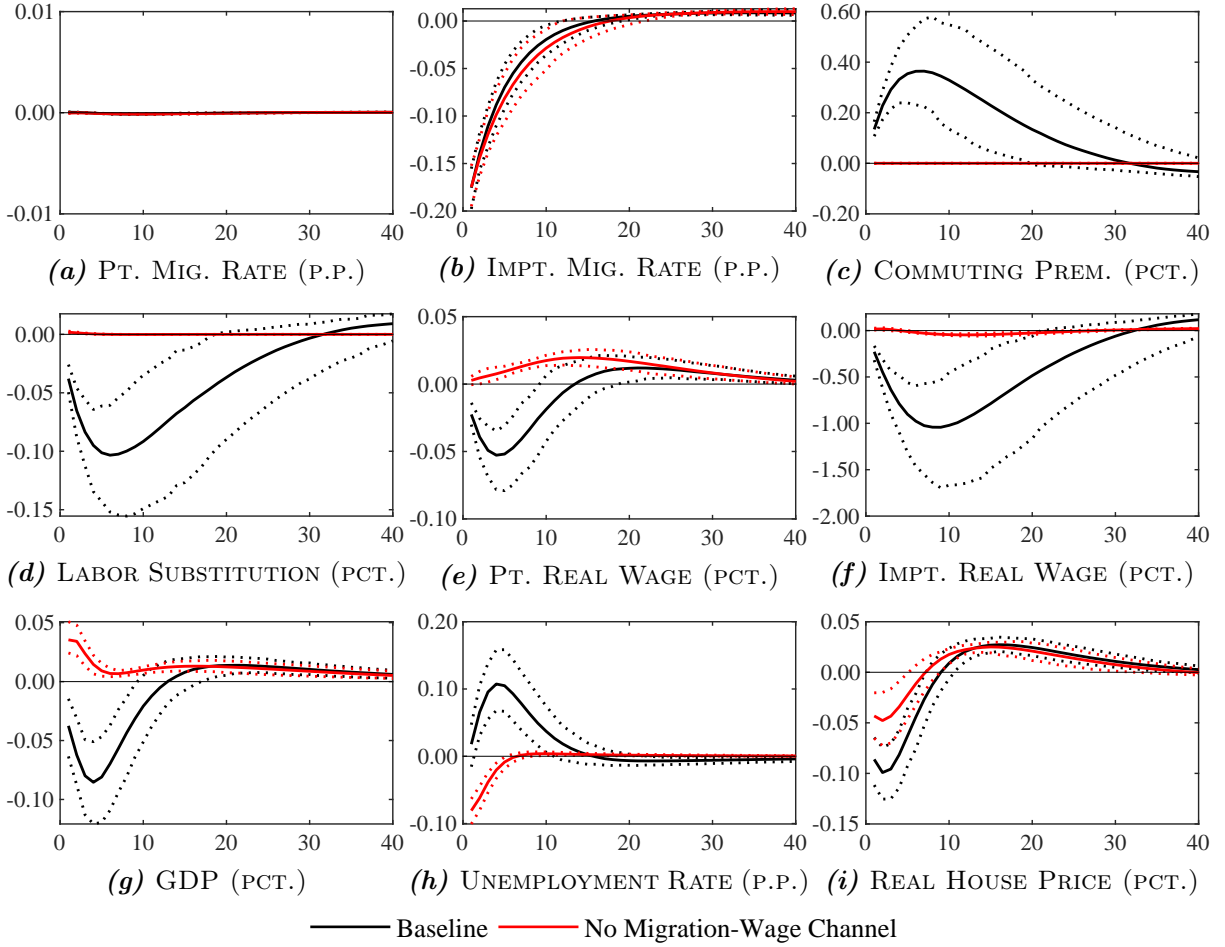
### 6.1 Relocation Preference and Housing Market Shocks

Figures 3-4 plot the impulse responses to a relocation preference shock and a collateral constraint shock, from the baseline and restricted estimations. A positive relocation preference shock increases the marginal disutility of relocating. Workers in both households who anticipate unemployment become less willing to accept long-distance job offers, pushing migration down. This forces the intermediate firm to pay a higher average commuting premium, since its workers, on average, live farther away from the firm's establishment. As a result, the firm reduces its spatial labor substitution, implying that it increasingly hires locally. Cross-area competition between workers for jobs falls, which leads the workers to target higher wage markups. Nominal and real wages consequently rise. The firm responds to this by reducing its labor demand, driving the economy into a contraction. In the restricted estimation without the migration-wage channel, the relocation preference shock does not have any considerable effects on wage inflation or GDP.

The baseline response of wage inflation to a drop in migration is slightly smaller in the



**Figure 4:** RESPONSES TO A NEGATIVE COLLATERAL CONSTRAINT SHOCK



*Note:* The figures plot the 5 pct. bound, median, and 95 pct. bound of the posterior impulse responses from the baseline and restricted estimations, following unit standard deviation shocks. Vertical axes measure deviations from the steady state.

model than in the New Keynesian Wage Phillips Curve in Section 3, albeit the difference is statistically indistinguishable at conventional confidence levels. Under specifications (3) and (6) in Table 1, a 0.05 p.p. drop in the migration rate causes a 0.05 p.p. increase in wage inflation. By comparison, in Figure 3, a 0.05 p.p. drop in migration causes a 0.04 p.p. increase in wage inflation. In both cases, the response is a combination of a response to lower migration in the *current* period and an anticipation that *future* migration will remain low.<sup>20</sup>

A negative collateral constraint shock lowers the loan-to-value limit. Internal migration declines for two reasons. First, for a given level of housing wealth, relocating impatient workers may not leverage themselves to the same extent as previously. Second, house prices decline, since refinancing impatient homeowners demand less housing, due to the diminished ability of houses to act as collateral. Because of both mechanisms, impatient workers are not able to refinance without lowering their consumption expenditures, making

<sup>20</sup>This anticipation stems from the AR(1) structure of the reduced-form representation of the migration rate in (3) and the AR(1) structure of the shock process in Subsection 4.8.

them less willing to accept long-distance job offers. If the migration-wage channel is active, analogously to the relocation preference shock, the decline in the impatient household's relocation propensity prompts the intermediate firm to avoid paying too high commuting premia by increasingly hiring locally. The resulting higher real wage and lower employment of impatient workers also cause the demand for patient workers to fall. The economy consequently goes into a contraction. If the migration-wage channel is inactive, the spill-over effects of the collateral constraint shock are very limited. The effects only relate to the repayment of loans. The economy expands slightly, since the patient household becomes more liquid, causing it to increase its demand for goods and housing.

The impulse responses yield important advice to macroprudential policymakers. Shifts in loan-to-value limits may, at first sight, not appear to have large effects on GDP and employment, since these changes only directly affect the small share of refinancing homeowners. However, this conclusion is misguided, since it does not consider the spill-over effects on migration, commuting, and wage setting. Several academics and policymakers have recently argued to reduce the amplitude of the housing-financial cycle through an introduction of countercyclical loan-to-value limits.<sup>21</sup> The impulse responses in Figure 4 provide an additional rationale for such a policy. Countercyclical loan-to-value limits can – through the migration-wage channel – reduce the countercyclicality of desired wage markups and make wages more procyclical. This will moderate the cyclical fluctuations in (un)employment, since a larger share of the cyclical adjustments at the labor market will be facilitated through adjustments in wages.

**How Do the Effects of Labor Migration Relate to Other Contributions?** The macroeconomic effects of lower labor migration are similar to the effects of lower migration in [Bhaskar et al. \(2002\)](#). There, workers are heterogeneous because of heterogeneity in locations and migration costs. This worker heterogeneity causes oligopsonistic firms, which hire the workers, to face upward-sloping labor supply curves. A reduction in labor migration (i.e., more worker heterogeneity) steepens the labor supply curve, which, in equilibrium, causes the real wage to rise and employment to fall.

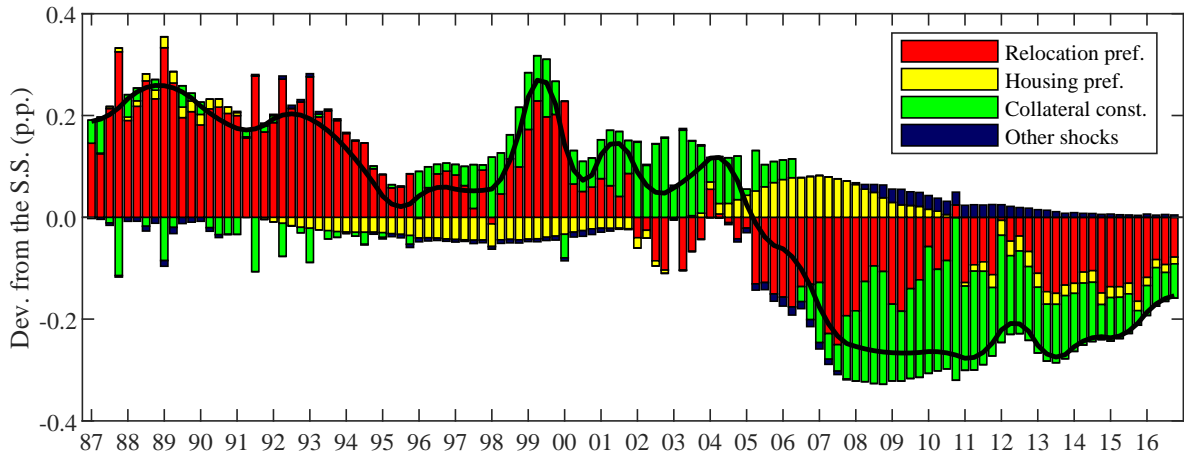
The effects of migration on the spatial wage dispersion and Pareto efficiency of the economy are identical to the effects of migration in [Topel \(1986\)](#), [Blanchard and Katz \(1992\)](#), and [Beaudry et al. \(2014\)](#). This is evident from the local labor demand functions, which dictate that less labor substitution causes the firm to increase its labor demand in high-wage areas (areas where  $\frac{w_t(k)}{w_t} > 1$ ) and reduce its labor demand in low-wage areas (areas where  $\frac{w_t(k)}{w_t} < 1$ ):

$$n_t(k) = \left( \frac{w_t(k)}{w_t} \right)^{-e_{w,t}} n_t \quad \text{and} \quad n'_t(k) = \left( \frac{w'_t(k)}{w'_t} \right)^{-e'_{w,t}} n'_t.$$

---

<sup>21</sup>See, e.g., the [Committee on the Global Financial System \(2010\)](#), the [IMF \(2011\)](#), [Lambertini et al. \(2013\)](#), and [Jensen et al. \(2018\)](#).

**Figure 5:** HISTORICAL SHOCK DECOMPOSITION OF THE MIGRATION RATE



*Note:* The decomposition is performed at the baseline posterior mode. Each bar indicates the contribution of the respective shock(s) to the migration rate. Hence, in each quarter, the sum of the four bars equals the migration rate.

This increases the wage dispersion, and compounds the distortions that are generated by workers' monopolistic competition, in keeping with the previous contributions. The economy is consequently brought further away from its Pareto efficient allocation.

The model captures the negative empirical relationship between migration and wages, unlike models with spatial search and matching. In these models, adverse housing preference and credit shocks cause the firm-owning patient household to cut back on its goods consumption, implying a decrease in the household's stochastic discount factor. The firm responds by posting fewer vacancies, since the value of a worker-firm match is discounted more heavily. In [Sterk \(2015\)](#), this does not affect the real wage, since it is exogenous. If the real wage instead was determined by Nash bargaining, following the argument in [Cahuc, Carcillo, and Zylberberg \(2014, Ch. 9\)](#), the reduction in the stochastic discount factor and total surplus would generate a drop in the real wage, even more at odds with the data.

The result that a reduction in migration (stemming from the housing market) increases the wage and unemployment levels is moreover in line with the [Oswald \(1996\)](#) hypothesis and the literature supporting this hypothesis (e.g., [Nickell and Layard, 1999](#); [Green and Hendershott, 2001](#)). Lastly, the model offers an explanation of the countercyclicality of wage markups, which [Karabarbounis \(2014\)](#) finds. To see this, note that because migration is procyclical, the desired wage markups will be countercyclical in the model.

## 6.2 What Drives Internal Migration?

I now examine the historical drivers of internal migration through the lenses of a shock decomposition of the migration rate, as shown in [Figure 5](#). The annualized cross-county migration rate of homeowners declined by 0.4 p.p. or 12 pct. from 1987 to 2000. 68 pct. of the decline (corresponding to 0.28 p.p.) is accounted for by initially negative relocation

preference shocks that gradually turned positive. This monotonic decay in the preference of workers for relocating suggests that the decline in migration has a long-run nature which is unrelated to the cyclical employment motive of the model. The relocation preference shocks have remained roughly stationary since 2000, implying that the exogenous long-run decline in migration ended in the beginning of the 2000s.

The annualized migration rate again declined from 2005 to 2010; this time by 1.0 p.p. or 37 pct. 83 pct. of this more rapid decline was due to collateral constraint shocks, which hindered mortgage refinancing by lowering house prices and loan-to-value limits. 14 pct. was additionally due to housing preference shocks, which further depressed house prices. This relatively low contribution of housing preference shocks contrasts [Sterk \(2015\)](#), who conjectures that these shocks explain almost the entire recent decline in migration, using a calibrated model with housing preference and technology shocks. However, the estimation finds that such a large contribution from housing preference shocks is not probable, though it is, *a priori*, possible also in my model.

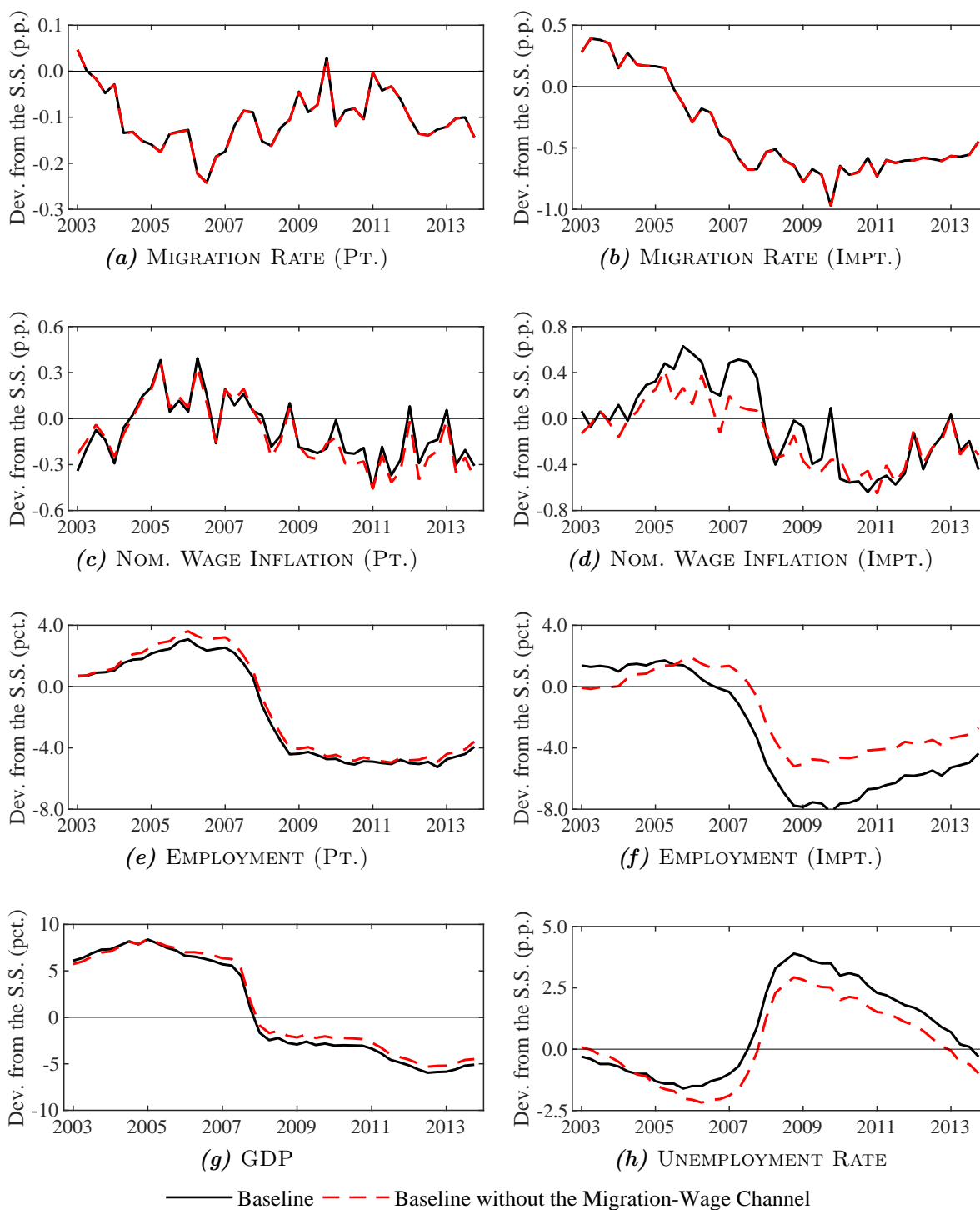
### 6.3 The Migration-Wage Channel and the Great Recession

This subsection examines the role of the migration-wage channel in accounting for the Great Recession. [Figure 6](#) plots the reactions of two versions of the model to the estimated sequence of shocks from the baseline estimation. With the first version, the baseline model is simply calibrated to the baseline posterior mode, implying an active migration-wage channel. In this simulation, the observed variables, by construction, match the data. Furthermore, one can recover the implied historical paths of all unobserved variables, including disaggregated household variables. With the second version, the model is also calibrated to the baseline posterior mode, but the proximity shares in [\(15\)](#) are set to their steady-state values, so that migration does not exercise a direct effect on wage setting.

GDP dropped by 10.0 pct., while the unemployment rate rose by 5.5 p.p., from 2006Q4 to 2009Q4. 0.50 p.p. and 0.55 p.p. of these recessionary movements can be traced to the migration-wage channel. Thus, in the setting without the channel, GDP only drops by 9.5 pct., and the unemployment rate only rises by 4.95 p.p. The size of the estimated effect on unemployment is close to the measure in [Sterk \(2015\)](#), in which the drop in migration accounts of a 0.6 p.p. increase in the unemployment rate. Regardless of the migration-wage channel, the recession causes some wage disinflation through the usual Phillips curve slack mechanism. The magnitude of the wage disinflation, however, depends on the migration-wage channel. As the migration of impatient workers fell, the associated increase in commuting premia and drop in labor substitution, dampened the disinflation in impatient workers' wages. The resulting higher real wage exacerbated the cutback in demand for impatient workers. This, in turn, amplified the drop in demand for patient workers and the contraction as a whole.

[Subsection 6.2](#) showed that migration was predominantly driven by housing market shocks around the Great Recession. The model hence ascribes a considerably larger part to

**Figure 6:** HISTORICAL AND COUNTERFACTUAL PATHS AROUND THE GREAT RECESSION



*Note:* Each figure plots the paths of an endogenous variable when the model is calibrated to the baseline posterior mode and the baseline posterior mode excluding the migration-wage channel.

housing market shocks in explaining the recession if the migration-wage channel is active. The gaps between the variables in each subfigure of Figure 6 highlight the extent to which the model fails to capture a portion of the Great Recession without the migration-wage

channel. This channel formally affects wage setting through the New Keynesian Wage Phillips Curves. Consequently, without the channel, the estimation must excessively rely on wage markup shocks in order for the model to match the data.<sup>22</sup> Without the migration-wage channel, the real wage of the impatient household becomes too low, leaving labor demand to be too high. The prevalence of large positive wage markups during and after the Great Recession has previously been noted by [Karabarbounis \(2014\)](#), using a different identification strategy. He finds that the cyclical component of the average wage markup increased by 14 pct. from 2006 to 2010.

## 7 Concluding Remarks

The linkage between internal migration, commuting, and wage setting which the chapter proposes has, until now, been unexplored in the business cycle literature. The estimation demonstrates that declining migration – through an increase in commuting premia and a narrowing of the areas in which firms hire workers – imposes real wage rigidities that amplify contractions. Policymakers should have this in mind when deciding on structural and stabilization policies that influence labor migration. The chapter additionally contributes to an understanding of the decline in the migration of homeowners since 1987. The estimation shows that the gradual decline prior to 2000 is best understood as a long-run phenomenon. The estimation also shows that the more rapid decline from 2005 to 2010 can be explained by a mortgage lock-in, due to adverse housing demand and credit shocks.

Two directions of further research appear from the analysis. One direction is to combine search unemployment under spatial matching and the migration-wage channel. In a resulting framework, the macroeconomic consequences of fluctuating migration rates can potentially be much larger if the effects of spatial matching and migration-dependent wage setting amplify each other. Another direction of further research is to introduce rental housing markets into stochastic business cycle models with relocations. In such a framework, the consequences of house prices slumps on migration may be smaller if some workers have the option of defaulting on their mortgage loans and then relocating.

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<sup>22</sup>[Chari, Kehoe, and McGrattan \(2009\)](#) forcefully criticize the extent to which New Keynesian models rely on wage markup shocks when explaining macroeconomic fluctuations.

## A Appendix: Derivation of the Reduced-Form New Keynesian Wage Phillips Curve

The reduced-form representation of the New Keynesian Wage Phillips Curve is derived from the following system of equations:

$$\pi_{W,t} = \tilde{\gamma}_W \pi_{P,t-1} + \tilde{\beta} \mathbb{E}_t \{ \pi_{W,t+1} - \tilde{\gamma}_W \pi_{P,t} \} - \tilde{\lambda}_W \tilde{\varphi} u_t + \tilde{\kappa}_M f(m_t) + s_{W,t}, \quad (\text{A.1})$$

$$u_t = \varsigma_U u_{t-1} + v_{U,t}, \quad (\text{A.2})$$

$$f(m_t) = \varsigma_M f(m_{t-1}) + v_{M,t}, \quad (\text{A.3})$$

where  $\mathbb{E}\{s_{W,t+1}\} = \mathbb{E}\{v_{U,t+1}\} = \mathbb{E}\{v_{M,t+1}\} = 0$ . The reduced-form New Keynesian Wage Phillips Curve is

$$\pi_{W,t} = \tilde{\gamma}_W \pi_{P,t-1} + \sigma_U u_t + \sigma_M f(m_t) + s_{W,t}. \quad (\text{A.4})$$

I now show that (A.4) is the solution to the system consisting of (A.1)-(A.3), using the method of undetermined coefficients.

First, bring (A.4) one period forward and take the expectation conditional on period  $t$ ,

$$\begin{aligned} \mathbb{E}_t \{ \pi_{W,t+1} \} &= \tilde{\gamma}_W \pi_{P,t} + \sigma_U \mathbb{E}_t \{ u_{t+1} \} + \sigma_M \mathbb{E}_t \{ f(m_{t+1}) \} + \mathbb{E}_t \{ s_{W,t+1} \} \\ &= \tilde{\gamma}_W \pi_{P,t} + \sigma_U \varsigma_U u_t + \sigma_M \varsigma_M f(m_t), \end{aligned} \quad (\text{A.5})$$

where the second line arises from the substitution of (A.2)-(A.3) and  $\mathbb{E}_t \{ s_{W,t+1} \} = \mathbb{E}_t \{ v_{U,t+1} \} = \mathbb{E}_t \{ v_{M,t+1} \} = 0$ .

Next, substituting (A.5) into (A.1) gives

$$\begin{aligned} \pi_{W,t} &= \tilde{\gamma}_W \pi_{P,t-1} + \tilde{\beta} [ \tilde{\gamma}_W \pi_{P,t} + \sigma_U \varsigma_U u_t + \sigma_M \varsigma_M f(m_t) - \tilde{\gamma}_W \pi_{P,t} ] - \tilde{\lambda}_W \tilde{\varphi} u_t + \tilde{\kappa}_M f(m_t) + s_{W,t} \\ &= \tilde{\gamma}_W \pi_{P,t-1} + [ \tilde{\beta} \sigma_U \varsigma_U - \tilde{\lambda}_W \tilde{\varphi} ] u_t + [ \tilde{\beta} \sigma_M \varsigma_M + \tilde{\kappa}_M ] f(m_t) + s_{W,t}. \end{aligned} \quad (\text{A.6})$$

Finally, it is evident that (A.4) is the solution to the system consisting of (A.1)-(A.3) by comparing (A.4) and (A.6) if and only if

$$\begin{aligned} \tilde{\gamma}_W &= \tilde{\gamma}_W, \\ \sigma_U &= \tilde{\beta} \sigma_U \varsigma_U - \tilde{\lambda}_W \tilde{\varphi}, \\ \sigma_M &= \tilde{\beta} \sigma_M \varsigma_M + \tilde{\kappa}_M. \end{aligned}$$

Solving this  $3 \times 3$  system for the three unknowns,  $(\tilde{\gamma}_W, \sigma_U, \sigma_M)$ , yields

$$\begin{aligned}\tilde{\gamma}_W &= \tilde{\gamma}_W, \\ \sigma_U &= -\frac{\tilde{\lambda}_W \tilde{\varphi}}{1 - \tilde{\beta}_{\zeta_U}}, \\ \sigma_M &= \frac{\tilde{\kappa}_M}{1 - \tilde{\beta}_{\zeta_M}}.\end{aligned}$$



## B Appendix: Dynamic Equilibrium Conditions

### Patient Household

The patient household maximizes its utility function,

$$\mathbb{E}_0 \left\{ \sum_{t=0}^{\infty} \beta^t s_{I,t} \left[ \Xi \log(c_t - \eta c_{t-1}) + \omega_H s_{H,t} \log(h_t) - \frac{s_{L,t}}{1+\varphi} l_t^{1+\varphi} - \frac{\omega_R s_{R,t}}{1+\chi} m_t^{1+\chi} \right] \right\}, \quad (\text{B.1})$$

subject to a budget constraint,

$$\begin{aligned} c_t + q_t h_t + \frac{R_{t-1}}{1+\pi_{P,t}} b_{t-1} + \frac{k_t}{s_{AK,t}} + \frac{f(z_t)}{s_{AK,t}} k_{t-1} + \frac{g(k_t, k_{t-1})}{s_{AK,t}} k_{t-1} + v_t + p_{X,t} x_t + \alpha s_{G,t} \\ = (1 - u_{a,t}) w_t l_t + u_{a,t} m_{u,t} w_t l_t + div v_t + (1 - \delta_H) q_t h_{t-1} + b_t \\ + \left( r_{K,t} z_t + \frac{1 - \delta_K}{s_{AK,t}} \right) k_{t-1} + p_{V,t} v_t + (r_{X,t} + p_{X,t}) x_{t-1}, \end{aligned} \quad (\text{B.2})$$

and to the expression for the average internal migration rate of all workers,

$$\begin{aligned} m_t &\equiv (1 - u_{a,t}) \cdot 0 + u_{a,t} m_{u,t} \\ &= u_{a,t} m_{u,t}, \end{aligned} \quad (\text{B.3})$$

where  $\Xi \equiv \frac{1-\eta}{1-\beta\eta}$ ,  $f(z_t) \equiv r_K \left[ \frac{1}{2} \frac{\zeta}{1-\zeta} z_t^2 + \left(1 - \frac{\zeta}{1-\zeta}\right) z_t + \frac{1}{2} \frac{\zeta}{1-\zeta} - 1 \right]$ , and  $g(k_t, k_{t-1}) \equiv \frac{\iota}{2} \left( \frac{k_t}{k_{t-1}} - 1 \right)^2$ .

The marginal utility of goods consumption ( $u_{c,t}$ ) is

$$u_{c,t} \equiv \frac{1-\eta}{1-\beta\eta} \left[ \frac{s_{I,t}}{c_t - \eta c_{t-1}} - \beta\eta \frac{s_{I,t+1}}{c_{t+1} - \eta c_t} \right].$$

The patient household maximizes its utility function with respect to housing, labor supply, the internal migration rate of workers who anticipate unemployment, net borrowing, nonresidential capital, the utilization rate of nonresidential capital, intermediate housing inputs, and land. The resulting first-order conditions are

$$u_{c,t}q_t = s_{I,t}s_{H,t}\frac{\omega_H}{h_t} + \beta\mathbb{E}_t\{u_{c,t+1}(1 - \delta_H)q_{t+1}\}, \quad (\text{B.4})$$

$$[1 - u_{a,t} + u_{a,t}m_{u,t}]u_{c,t}w_t = s_{I,t}s_{L,t}l_t^\varphi, \quad (\text{B.5})$$

$$u_{c,t}w_t l_t = \omega_{RSR,t}s_{I,t}(u_{a,t}m_{u,t})^\chi, \quad (\text{B.6})$$

$$u_{c,t} = \beta\mathbb{E}_t\left\{u_{c,t+1}\frac{R_t}{1 + \pi_{P,t+1}}\right\}, \quad (\text{B.7})$$

$$\begin{aligned} & \frac{u_{c,t}}{s_{AK,t}} \left[ 1 + \iota \left( \frac{\hat{k}_t}{\hat{k}_{t-1}} - 1 \right) \right] \\ & = \beta\mathbb{E}_t \left\{ u_{c,t+1} \left[ r_{K,t+1}z_{t+1} + \frac{1 - \delta_K}{s_{AK,t+1}} - \frac{f(z_{t+1})}{s_{AK,t+1}} + \frac{\iota}{2} \left( \frac{\hat{k}_{t+1}^2}{\hat{k}_t^2} - 1 \right) \frac{1}{s_{AK,t+1}} \right] \right\}, \end{aligned} \quad (\text{B.8})$$

$$r_{K,t} = \frac{f'(z_t)}{s_{AK,t}}, \quad (\text{B.9})$$

$$p_{V,t} = 1, \quad (\text{B.10})$$

$$u_{c,t}p_{X,t} = \beta\mathbb{E}_t\{u_{c,t+1}(r_{X,t+1} + p_{X,t+1})\}. \quad (\text{B.11})$$

## Impatient Household

The impatient household maximizes its utility function,

$$\mathbb{E}_0 \left\{ \sum_{t=0}^{\infty} \beta^t s_{I,t} \left[ \Xi' \log(c'_t - \eta c'_{t-1}) + \omega_H s_{H,t} \log(h'_t) - \frac{s_{L,t}}{1+\varphi} l_t^{1+\varphi} - \frac{\omega_R s_{R,t}}{1+\chi} m_t^{1+\chi} \right] \right\}, \quad (\text{B.12})$$

subject to a budget constraint,

$$\begin{aligned} c'_t + q_t h'_t + \frac{R_{t-1}}{1+\pi_{P,t}} b'_{t-1} + (1-\alpha) s_{G,t} \\ = (1-u'_{a,t}) w'_t l'_t + u'_{a,t} m'_{u,t} w'_t l'_t + (1-\delta_H) q_t h'_{t-1} + b'_t, \end{aligned} \quad (\text{B.13})$$

to the expression for the average internal migration rate of all workers,

$$\begin{aligned} m'_t &\equiv (1-u'_{a,t}) \cdot 0 + u'_{a,t} m'_{u,t} \\ &= u'_{a,t} m'_{u,t}, \end{aligned} \quad (\text{B.14})$$

and to a refinancing collateral constraint,

$$\begin{aligned} b'_t \leq (1-m'_t) \left( (1-\rho) \frac{b'_{t-1}}{1+\pi_{P,t}} + \rho \xi_{S_{C,t}} \mathbb{E}_t \left\{ \frac{(1+\pi_{P,t+1}) q_{t+1} h'_t}{R_t} \right\} \right) \\ + m'_t \xi_{S_{C,t}} \mathbb{E}_t \left\{ \frac{(1+\pi_{P,t+1}) q_{t+1} h'_t}{R_t} \right\}, \end{aligned} \quad (\text{B.15})$$

where  $\Xi' \equiv \frac{1-\eta}{1-\beta'\eta}$ .

I solve the utility maximization problem through the method of Lagrange multipliers. The associated Lagrange function before substitution of (B.13) is

$$\begin{aligned} \mathbb{E}_0 \left\{ \sum_{t=0}^{\infty} \beta^t s_{I,t} \left[ \Xi' \log(c'_t - \eta c'_{t-1}) + \omega_H s_{H,t} \omega \log(h'_t) - \frac{s_{L,t}}{1+\varphi} l_t^{1+\varphi} - \frac{\omega_R s_{R,t}}{1+\chi} (u'_{a,t} m'_{u,t})^{1+\chi} \right. \right. \\ \left. \left. + \lambda_t \left[ (1-u'_{a,t} m'_{u,t}) \left( (1-\rho) \frac{b'_{t-1}}{1+\pi_{P,t}} + \rho \xi_{S_{C,t}} \mathbb{E}_t \left\{ \frac{(1+\pi_{P,t+1}) q_{t+1} h'_t}{R_t} \right\} \right) \right. \right. \right. \\ \left. \left. \left. + u'_{a,t} m'_{u,t} \xi_{S_{C,t}} \mathbb{E}_t \left\{ \frac{(1+\pi_{P,t+1}) q_{t+1} h'_t}{R_t} \right\} - b'_t \right] \right] \right\}, \end{aligned}$$

where  $\lambda_t$  denotes the multiplier on (B.15).

The marginal utility of goods consumption ( $u'_{c,t}$ ) is

$$u'_{c,t} \equiv \frac{1-\eta}{1-\beta'\eta} \left[ \frac{s_{I,t}}{c'_t - \eta c'_{t-1}} - \beta' \eta \frac{s_{I,t+1}}{c'_{t+1} - \eta c'_t} \right].$$

The impatient household maximizes its utility function with respect to housing, labor supply, the internal migration rate of workers who anticipate unemployment, and net borrowing. The resulting first-order conditions are

$$u'_{c,t}q_t = s_{I,t}s_{H,t}\frac{\omega_H}{h'_t} + \beta'\mathbb{E}_t\{u'_{c,t+1}(1 - \delta_H)q_{t+1}\} + s_{I,t}\lambda_t[(1 - u'_{a,t}m'_{u,t})\rho + u'_{a,t}m'_{u,t}]\xi_{SC,t}\mathbb{E}_t\left\{\frac{(1 + \pi_{P,t+1})q_{t+1}}{R_t}\right\}, \quad (\text{B.16})$$

$$[1 - u'_{a,t} + u'_{a,t}m'_{u,t}]u'_{c,t}w'_t = s_{I,t}s_{L,t}l'^{\varphi}_t, \quad (\text{B.17})$$

$$u'_{c,t}w'_t l'_t = \omega_R s_{R,t} s_{I,t} (u'_{a,t} m'_{u,t})^\chi - (1 - \rho) s_{I,t} \lambda_t \left[ \xi_{SC,t} \mathbb{E}_t \left\{ \frac{(1 + \pi_{P,t+1}) q_{t+1} h'_t}{R_t} \right\} - \frac{b'_{t-1}}{1 + \pi_{P,t}} \right], \quad (\text{B.18})$$

$$u'_{c,t} + \beta'(1 - \rho)\mathbb{E}_t\left\{s_{I,t+1}\lambda_{t+1}\frac{1 - u'_{s,t+1}m'_{u,t+1}}{1 + \pi_{P,t}}\right\} = \beta'\mathbb{E}_t\left\{u'_{c,t+1}\frac{R_t}{1 + \pi_{P,t+1}}\right\} + s_{I,t}\lambda_t. \quad (\text{B.19})$$

## Intermediate Firm

The intermediate firm maximizes its profits,

$$\frac{Y_t}{M_{P,t}} + q_t I_{H,t} - w_t n_t - w'_t n'_t - r_{K,t} z_t k_{t-1} - p_{V,t} v_t - r_{X,t} x_{t-1}, \quad (\text{B.20})$$

subject to the goods production and housing transformation technologies,

$$Y_t = (z_t k_{t-1})^\mu (s_{Y,t} n_t^\alpha n'_t)^{1-\alpha} \quad (\text{B.21})$$

$$I_{H,t} = v_t^\nu x_{t-1}^{1-\nu}, \quad (\text{B.22})$$

to the law-of-motion for the total real wage of the patient workers,

$$\begin{aligned} w_t &\equiv f(e_{W,t}) \tilde{w}_t \\ &= f(e_{W,t}) [\tilde{w}_{t-1} + \tilde{\pi}_{W,t} - \pi_{P,t}] \\ &= f(e_{W,t}) \left[ \tilde{w}_{t-1} + \gamma_W \pi_{P,t-1} + \beta \mathbb{E}_t \{ \tilde{\pi}_{W,t+1} - \gamma_W \pi_{P,t} \} \right. \\ &\quad \left. - \frac{(1 - \theta_W)(1 - \beta \theta_W)}{\theta_W(1 + e_{W,t} \varphi)} \left( \log M_{W,t} - \frac{1}{e_{W,t}} \right) + s_{W,t} - \pi_{P,t} \right], \end{aligned}$$

and to the law-of-motion for the total real wage of the impatient workers,

$$\begin{aligned} w'_t &\equiv f(e'_{W,t}) \tilde{w}'_t \\ &= f(e'_{W,t}) [\tilde{w}'_{t-1} + \tilde{\pi}'_{W,t} - \pi_{P,t}] \\ &= f(e'_{W,t}) \left[ \tilde{w}'_{t-1} + \gamma_W \pi_{P,t-1} + \beta' \mathbb{E}_t \{ \tilde{\pi}'_{W,t+1} - \gamma_W \pi_{P,t} \} \right. \\ &\quad \left. - \frac{(1 - \theta_W)(1 - \beta' \theta_W)}{\theta_W(1 + e'_{W,t} \varphi)} \left( \log M'_{W,t} - \frac{1}{e'_{W,t}} \right) + s_{W,t} - \pi_{P,t} \right], \end{aligned}$$

where  $\log M_{W,t}^D \equiv \log \frac{e_{W,t}}{e_{W,t-1}} \approx \frac{1}{e_{W,t}}$  and  $\log M'_{W,t} \equiv \log \frac{e'_{W,t}}{e'_{W,t-1}} \approx \frac{1}{e'_{W,t}}$ .

The intermediate firm maximizes its profits with respect to nonresidential capital, employment from the patient household, employment from the impatient household, intermediate housing inputs, land, labor substitution of patient workers, and labor substitution of impatient workers. The resulting first-order conditions are

$$\mu \frac{Y_t}{M_{P,t} k_{t-1}} = r_{K,t} z_t, \quad (\text{B.23})$$

$$(1 - \mu) \alpha \frac{Y_t}{M_{P,t} n_t} = w_t, \quad (\text{B.24})$$

$$(1 - \mu)(1 - \alpha) \frac{Y_t}{M_{P,t} n'_t} = w'_t, \quad (\text{B.25})$$

$$v_t = \nu q_t I_{H,t}, \quad (\text{B.26})$$

$$r_{X,t} = (1 - \nu) q_t I_{H,t}, \quad (\text{B.27})$$

$$\begin{aligned} & f'(e_{W,t}) [\tilde{w}_{t-1} + \tilde{\pi}_{W,t} - \pi_{P,t}] \\ &= f(e_{W,t}) \frac{(1 - \theta_W)(1 - \beta \theta_W)}{\theta_W(1 + e_{W,t} \varphi)} \left[ \frac{1}{e_{W,t}^2} - \frac{\varphi}{1 + e_{W,t} \varphi} \left( \log M_{W,t} - \frac{1}{e_{W,t}} \right) \right], \end{aligned} \quad (\text{B.28})$$

$$\begin{aligned} & f'(e'_{W,t}) [\tilde{w}'_{t-1} + \tilde{\pi}'_{W,t} - \pi_{P,t}] \\ &= f(e'_{W,t}) \frac{(1 - \theta_W)(1 - \beta' \theta_W)}{\theta_W(1 + e'_{W,t} \varphi)} \left[ \frac{1}{e'^2_{W,t}} - \frac{\varphi}{1 + e'_{W,t} \varphi} \left( \log M'_{W,t} - \frac{1}{e'_{W,t}} \right) \right], \end{aligned} \quad (\text{B.29})$$

where (B.26) follows from applying (B.10), and (B.27) follows from the normalization  $x_t = 1, \forall t$ .

## Household Constraints and Market-Clearing Conditions

The ex post budget constraint of the patient household is

$$\begin{aligned}
c_t + q_t h_t + \frac{R_{t-1}}{1 + \pi_{P,t}} b_{t-1} + \frac{k_t}{s_{AK,t}} + \frac{f(z_t)}{s_{AK,t}} k_{t-1} + \frac{g(k_t, k_{t-1})}{s_{AK,t}} k_{t-1} + v_t + p_{X,t} x_t + \alpha s_{G,t} \\
= w_t n_t + div_t + (1 - \delta_H) q_t h_{t-1} + b_t \\
+ \left( r_{K,t} z_t + \frac{1 - \delta_K}{s_{AK,t}} \right) k_{t-1} + p_{V,t} v_t + (r_{X,t} + p_{X,t}) x_{t-1}.
\end{aligned} \tag{B.30}$$

The ex post budget constraint of the impatient household is

$$\dot{c}_t + q_t h'_t + \frac{R_{t-1}}{1 + \pi_{P,t}} b'_{t-1} + (1 - \alpha) s_{G,t} = w'_t n'_t + (1 - \delta_H) q_t h'_{t-1} + b'_t. \tag{B.31}$$

The goods market clearing condition is

$$c_t + \dot{c}_t + \frac{k_t - (1 - \delta_K) k_{t-1}}{s_{AK,t}} + \frac{f(z_t)}{s_{AK,t}} k_{t-1} + \frac{g(k_t, k_{t-1})}{s_{AK,t}} k_{t-1} + v_t + s_{G,t} = Y_t. \tag{B.32}$$

The housing market clearing condition is

$$h_t + h'_t - (1 - \delta_H)(h_{t-1} + h'_{t-1}) = I_{H,t}. \tag{B.33}$$

The loan market clearing condition is

$$b_t = -b'_t. \tag{B.34}$$

### Labor Market Equilibrium

The labor market equilibrium conditions are

$$n_t = (1 - u_{a,t}) l_t + u_{a,t} m_{u,t} l_t, \tag{B.35}$$

$$n'_t = (1 - u'_{a,t}) l'_t + u'_{a,t} m'_{u,t} l'_t. \tag{B.36}$$

The unemployment rates are from (B.35) and (B.36)

$$\begin{aligned}
u_t &\equiv 1 - \frac{n_t}{l_t} \\
&= 1 - (1 - u_{a,t} + u_{a,t}m_{u,t}) \\
&= (1 - m_{u,t})u_{a,t},
\end{aligned} \tag{B.37}$$

$$\begin{aligned}
u'_t &\equiv 1 - \frac{n'_t}{l'_t} \\
&= 1 - (1 - u'_{a,t} + u'_{a,t}m'_{u,t}) \\
&= (1 - m'_{u,t})u'_{a,t}.
\end{aligned} \tag{B.38}$$

The total real wages that the workers receive are

$$w_t \equiv f(e_{W,t})\tilde{w}_t, \tag{B.39}$$

$$w'_t \equiv f(e'_{W,t})\tilde{w}'_t. \tag{B.40}$$

The commuting premium functions are

$$f(e_{W,t}) \equiv mi_t \cdot 0 + (1 - mi_t) \frac{\kappa}{1 + \psi} e_{W,t}^{1+\psi} - \psi e_{W,t} - \Upsilon, \tag{B.41}$$

$$f(e'_{W,t}) \equiv mi'_t \cdot 0 + (1 - mi'_t) \frac{\kappa}{1 + \psi} e'_{W,t}^{1+\psi} - \psi e'_{W,t} - \Upsilon', \tag{B.42}$$

where  $\Upsilon \equiv (1 - mi) \frac{\kappa}{1 + \psi} e_W^{1+\psi} - \psi e_W - 1$  and  $\Upsilon' \equiv (1 - mi') \frac{\kappa}{1 + \psi} e'_W^{1+\psi} - \psi e'_W - 1$ .

The proximity shares are

$$mi_t \equiv m_t + (1 - \sigma)mi_{t-1}, \tag{B.43}$$

$$mi'_t \equiv m'_t + (1 - \sigma)mi'_{t-1}. \tag{B.44}$$



## Identification of the Aggregate Average Wage Markup

Interpretation of unemployment and identification of the aggregate average wage markup are based on the Galí (2011) extension of the Erceg et al. (2000) labor market model. In the following, I derive the relationship between the unobserved wage markup and the observed unemployment rate, and show that expanding the model to account for internal migration does not change this relationship.

The first-order conditions of each household with respect to labor supply are

$$[1 - u_{a,t} + u_{a,t}m_{u,t}]u_{c,t}w_t = s_{I,t}s_{L,t}l_t^\varphi, \quad (\text{B.5})$$

$$[1 - u'_{a,t} + u'_{a,t}m'_{u,t}]u'_{c,t}w'_t = s_{I,t}s_{L,t}l_t'^\varphi. \quad (\text{B.17})$$

It is evident from (B.5) and (B.17) that the optimal choice of labor supply is associated with an equalization of the ex ante marginal rate of substitution to the perceived real wage:

$$MRS_{lc,t} \equiv \frac{s_{I,t}s_{L,t}l_t^\varphi}{u_{c,t}} = [1 - u_{a,t} + u_{a,t}m_{u,t}]f(e_{W,t+k})\tilde{w}_t \equiv \hat{w}_t, \quad (\text{B.45})$$

$$MRS'_{lc,t} \equiv \frac{s_{I,t}s_{L,t}l_t'^\varphi}{u'_{c,t}} = [1 - u'_{a,t} + u'_{a,t}m'_{u,t}]f(e_{W,t+k})\tilde{w}'_t \equiv \hat{w}'_t, \quad (\text{B.46})$$

where  $\hat{w}_t$  and  $\hat{w}'_t$  denote the perceived real wage. The perceived real wage is the real wage that the individual employed worker obtains after income sharing with unemployed workers. Thus, for unemployment rates above zero, the perceived real wage is lower than the actual wage. The corresponding ex post marginal rates of substitution of employment for goods consumption are defined as

$$MRS_{nc,t} \equiv \frac{s_{I,t}s_{L,t}n_t^\varphi}{u_{c,t}}, \quad (\text{B.47})$$

$$MRS'_{nc,t} \equiv \frac{s_{I,t}s_{L,t}n_t'^\varphi}{u'_{c,t}}. \quad (\text{B.48})$$

The unemployment rate measures are defined as

$$\exp(u_t) \equiv \frac{L_t}{N_t}, \quad (\text{B.49})$$

$$\exp(u'_t) \equiv \frac{L'_t}{N'_t}, \quad (\text{B.50})$$

where  $L_t$  denotes the labor force size, and  $N_t$  denotes the employment size. For unemployment rates near zero, these unemployment rate measures are very close to the conventional measure  $1 - \frac{N_t}{L_t}$ .<sup>1</sup>

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<sup>1</sup>To see this, note that  $1 - \frac{N_t}{L_t} = 1 - \frac{n_t}{l_t} = 1 - \exp(\log n_t - \log l_t) = 1 - \exp(-u_t) \simeq u_t$  for unemployment rates near zero.

The wage markups measure the gap between the perceived benefit and cost of employment. Hence, the average gross wage markups are defined as the gap between the perceived real wage and the ex post marginal rate of substitution:

$$\log M_{W,t} \equiv \log \hat{w}_t - \log MRS_{nc,t}, \quad (\text{B.51})$$

$$\log M'_{W,t} \equiv \log \hat{w}'_t - \log MRS'_{nc,t}. \quad (\text{B.52})$$

Inserting (B.45), (B.47), and (B.49) into (B.51), inserting (B.46), (B.48), and (B.50) into (B.52), and applying the definitions of the unemployment rates in (B.37) and (B.38) identifies the wage markups as

$$\log M_{W,t} = \varphi u_t, \quad (\text{B.53})$$

$$\log M'_{W,t} = \varphi u'_t. \quad (\text{B.54})$$

This identification of the wage markups is identical to the identification in Galí (2011). The wage markups are directly proportional to the unemployment rates, since more aggressive wage demands by workers reduce employment and increase labor force participation, thereby increasing the unemployment rate. The elasticities of marginal disutility of work are inversely proportional to the unemployment rates, since higher elasticities of marginal disutility of work imply a lower labor supply.

## C Appendix: Steady-State Computation

This appendix documents the derivation of the steady-state solution of the model. An exact numerical solution can be reached by combining the resulting relations as it is done in the steady-state code.

### Marginal Utility and Inflation

The marginal utilities of goods consumption are

$$\begin{aligned}
 u_c &= \frac{1-\eta}{1-\beta\eta} \left[ \frac{1}{c-\eta c} - \beta \frac{\eta}{c-\eta c} \right] & u'_c &= \frac{1-\eta}{1-\beta'\eta} \left[ \frac{1}{c'-\eta c'} - \beta' \frac{\eta}{c'-\eta c'} \right] \\
 &= \frac{1-\eta}{1-\beta\eta} \frac{1-\beta\eta}{1-\eta} \frac{1}{c} & \text{and} & & = \frac{1-\eta}{1-\beta'\eta} \frac{1-\beta'\eta}{1-\eta} \frac{1}{c'} \\
 &= \frac{1}{c} & & & = \frac{1}{c'}.
 \end{aligned}$$

The utilization rate of nonresidential capital is

$$z = 1.$$

Net price and wage inflation are

$$\pi_P = \pi_W = \pi'_W = 1.$$

### First-Order Conditions

The first-order condition of the patient household with respect to net borrowing ( $b_t$ ) is

$$\begin{aligned}
 u_c &= \beta u_c \frac{R}{1 + \pi_P} \\
 R &= \frac{1}{\beta}.
 \end{aligned}$$

The first-order condition of the patient household with respect to nonresidential capital ( $k_t$ ) is

$$\begin{aligned}
 u_c \left[ 1 + \iota \left( \frac{k}{k} - 1 \right) \right] &= \beta u_c \left[ r_K + 1 - \delta_K - \frac{\iota}{2} \left( \frac{k^2}{k^2} - 1 \right) \right] \\
 1 &= \beta [r_K + 1 - \delta_K] \\
 r_K &= R - [1 - \delta_K].
 \end{aligned} \tag{C.1}$$

The first-order condition of the intermediate firm with respect to nonresidential capital ( $k_t$ ) is

$$\mu \frac{Y_t}{M_P k} = r_K. \quad (\text{C.2})$$

Combining (C.1) and (C.2), one gets an expression for the  $\frac{k}{Y}$  ratio:

$$\begin{aligned} \mu \frac{Y}{M_P k} &= \frac{1}{\beta} - (1 - \delta_K) \\ \frac{Y}{k} &= \frac{1 - \beta(1 - \delta_K)}{\beta \mu} M_P \\ \frac{k}{Y} &= \frac{\beta \mu}{1 - \beta(1 - \delta_K)} \frac{1}{M_P} \equiv \aleph_1. \end{aligned} \quad (\text{C.3})$$

The first-order condition of the patient household with respect to housing ( $h_t$ ) is

$$\begin{aligned} u_c q &= \frac{\omega_H}{h} + \beta u_c (1 - \delta_H) q \\ \frac{1}{c} q &= \frac{\omega_H}{h} + \beta \frac{1}{c} (1 - \delta_H) q \\ \frac{qh}{c} &= \frac{\omega_H}{1 - \beta(1 - \delta_H)} \equiv \aleph_2. \end{aligned} \quad (\text{C.4})$$

The first-order condition of the impatient household with respect to net borrowing ( $b_t$ ) is

$$\begin{aligned} u'_c + \beta'(1 - \rho) \lambda \frac{1 - m'}{1 + \pi_P} &= \beta' u'_c \frac{R}{1 + \pi_P} + \lambda \\ \frac{1}{c'} + \beta'(1 - \rho) \lambda (1 - m') &= \beta' \frac{1}{c'} \frac{1}{\beta} + \lambda \\ \lambda &= \frac{1 - \frac{\beta'}{\beta}}{c' [1 - \beta'(1 - \rho)(1 - m')]} \end{aligned} \quad (\text{C.5})$$

The first-order condition of the impatient household with respect to housing ( $h'_t$ ) is

$$\begin{aligned} u'_c q &= \frac{\omega_H}{h'} + \beta u'_c (1 - \delta_H) q + \lambda [(1 - m') \rho + m'] \xi \frac{(1 + \pi_P) q}{R} \\ \frac{1}{c'} q &= \frac{\omega_H}{h'} + \beta' \frac{1}{c'} (1 - \delta_H) q + \frac{1 - \frac{\beta'}{\beta}}{c' [1 - \beta'(1 - m')(1 - \rho)]} [(1 - m') \rho + m'] \xi \frac{q}{\beta} \\ \frac{1}{c'} q h' &= \omega_H + \beta' \frac{1}{c'} (1 - \delta_H) q h' + \frac{\beta - \beta'}{c' [1 - \beta'(1 - m')(1 - \rho)]} [(1 - m') \rho + m'] \xi q h' \\ \frac{q h'}{c'} &= \frac{\omega_H}{1 - \beta'(1 - \delta_H) - \frac{\beta - \beta'}{1 - \beta'(1 - m')(1 - \rho)}} [(1 - m') \rho + m'] \xi \equiv \aleph_3. \end{aligned} \quad (\text{C.6})$$

The first-order condition of the intermediate firm with respect to intermediate housing inputs ( $v_t$ ) is

$$v = \nu q I_H. \quad (\text{C.7})$$

## Household Constraints and Market-Clearing Conditions

The collateral constraint is

$$b' = \xi \frac{qh'}{R}. \quad (\text{C.8})$$

The  $\frac{c'}{Y}$  ratio is from the budget constraint of the impatient household given by

$$\begin{aligned} c' + qh' + R \frac{b'}{1 + \pi} &= w'n' + (1 - \delta_H)qh' + b' \\ c' + \delta_H qh' &= w'n' - (R - 1) \frac{\xi}{R} qh' \\ c' + \delta_H qh' &= w'n' - \aleph_4 qh', \\ c' + \delta_H \aleph_3 c' &= (1 - \mu)(1 - \alpha) \frac{Y}{M_P n'} n' - \aleph_4 \aleph_3 c' \\ [1 + \delta_H \aleph_3 + \aleph_4 \aleph_3] c' &= (1 - \mu)(1 - \alpha) \frac{1}{M_P} Y \\ \frac{c'}{Y} &= \frac{\beth_5}{\beth_4}, \end{aligned} \quad (\text{C.9})$$

where  $\aleph_4 \equiv (R - 1) \frac{\xi}{R}$ ,  $\beth_4 \equiv 1 + \delta_H \aleph_3 + \aleph_4 \aleph_3$ , and  $\beth_5 \equiv (1 - \mu)(1 - \alpha) \frac{1}{M_P}$ .

The real house price is determined by the housing market equilibrium condition, as

$$\begin{aligned} I_H &= h + h' - (1 - \delta_H)(h + h') \\ qI_H &= \delta_H q(h + h') \\ qI_H &= \delta_H (\aleph_2 c + \aleph_3 c') \end{aligned} \quad (\text{C.10})$$

$$\frac{qI_H}{Y} = \delta_H \left( \aleph_2 \frac{c}{Y} + \aleph_3 \frac{c'}{Y} \right). \quad (\text{C.11})$$

The budget constraint of the patient household is from (B.30) given by

$$\begin{aligned} c + qh + \frac{R}{1 + \pi_P} b + k + v + p_X x \\ = wn + \left( 1 - \frac{1}{M_P} \right) Y + (1 - \delta_H)qh + b + (r_K + 1 - \delta_K)k + p_V v + (r_X + p_X)x. \end{aligned}$$

Rearranging and applying the loan market clearing condition in (B.34),  $p_V = 1$  from (B.10), and the normalization  $x = 1$  yields

$$c + \delta_H q h + k = w n + \left(1 - \frac{1}{M_P}\right) Y + (r_K + 1 - \delta_K) k + r_X + (R - 1) b'.$$

Rearranging and inserting the real net rental rate of nonresidential capital from (C.1), the real gross rental rate of land from (B.27), and the collateral constraint from (C.8) yields

$$\begin{aligned} c + \delta_H q h &= w n + \left(1 - \frac{1}{M_P}\right) Y + (R - (1 - \delta_K) + 1 - \delta_K - 1) k + (1 - \nu) q I_H + (R - 1) \xi \frac{q h'}{R} \\ c + \delta_H q h &= w n + \left(1 - \frac{1}{M_P}\right) Y + r k + (1 - \nu) q I_H + \aleph_4 q h' \end{aligned}$$

where  $r \equiv R - 1$  and  $\aleph_4 \equiv (R - 1) \frac{\xi}{R}$ . Substituting first (C.10) and (B.24) and then (C.3)-(C.6) into it gives

$$\begin{aligned} c + \delta_H q h &= (1 - \mu) \alpha \frac{Y}{M_P n} n + \left(1 - \frac{1}{M_P}\right) Y + r k + (1 - \nu) \delta_H q (h + h') + \aleph_4 q h' \\ c + \delta_H \aleph_2 c &= (1 - \mu) \alpha \frac{Y}{M_P n} n + \left(1 - \frac{1}{M_P}\right) Y + r \aleph_1 Y + (1 - \nu) \delta_H (\aleph_2 c + \aleph_3 c') + \aleph_4 \aleph_3 c' \\ [1 + \nu \delta_H \aleph_2] c - [\aleph_4 \aleph_3 + (1 - \nu) \delta_H \aleph_3] c' &= \left[ (1 - \mu) \alpha \frac{1}{M_P} + 1 - \frac{1}{M_P} + r \aleph_1 \right] Y \\ \beth_1 c - \beth_2 c' &= \beth_3 Y, \end{aligned} \tag{C.12}$$

where  $\beth_1 \equiv 1 + \nu \delta_H \aleph_2$ ,  $\beth_2 \equiv \aleph_4 \aleph_3 + (1 - \nu) \delta_H \aleph_3$ , and  $\beth_3 \equiv (1 - \mu) \alpha \frac{1}{M_P} + 1 - \frac{1}{M_P} + r \aleph_1$ . Finally, inserting (C.9) into the above expression gives an expression for the  $\frac{c}{Y}$  ratio:

$$\frac{c}{Y} = \frac{\beth_2 \beth_5 + \beth_3 \beth_4}{\beth_1 \beth_4}. \tag{C.13}$$

## Solutions for Endogenous Variables

### Employment and Average Geographical Mobility Rates

Employment from the patient household is from (B.5), (B.24), and (B.35) given by

$$\begin{aligned} \frac{1}{(1 - u) u_c} l^\varphi &= (1 - \mu) \alpha \frac{Y}{M_P n} \\ \frac{c}{1 - u} \left( \frac{n}{1 - u} \right)^\varphi &= (1 - \mu) \alpha \frac{1}{M_P n \frac{1}{Y}} \\ n &= \left( (1 - \mu) \alpha \frac{1}{M_P \frac{c}{Y}} \right)^{\frac{1}{1 + \varphi}} (1 - u). \end{aligned} \tag{C.14}$$

The average internal migration rate of the patient household is from (B.6), (B.24), and

(B.35) given by

$$\begin{aligned}
m &= u_a m_u \\
&= u_a \left( \frac{u_c w l}{\omega_R} \right)^{\frac{1}{x}} \frac{1}{u_a} \\
&= \left( (1 - \mu) \alpha \frac{1}{\omega_R M_P \frac{c}{Y}} \frac{l}{n} \right)^{\frac{1}{x}} \\
&= \left( (1 - \mu) \alpha \frac{1}{\omega_R M_P \frac{c}{Y}} \frac{1}{1 - u} \right)^{\frac{1}{x}}. \tag{C.15}
\end{aligned}$$

Employment from the impatient household is from (B.17), (B.25), and (B.36) given by

$$\begin{aligned}
\frac{1}{(1 - u') u'_c} l'^{\varphi} &= (1 - \mu)(1 - \alpha) \frac{Y}{M_P n'} \\
\frac{c'}{1 - u'} \left( \frac{n'}{1 - u'} \right)^{\varphi} &= (1 - \mu)(1 - \alpha) \frac{1}{M_P n' \frac{1}{Y}} \\
n' &= \left( (1 - \mu)(1 - \alpha) \frac{1}{M_P \frac{c'}{Y}} \right)^{\frac{1}{1 + \varphi}} (1 - u'). \tag{C.16}
\end{aligned}$$

The average internal migration rate of the impatient household is from (B.18), (B.25), and (B.36) given by

$$\begin{aligned}
m' &= u'_a m'_u \\
&= u'_a \left( \frac{u'_c w' l'}{\omega_R} \right)^{\frac{1}{x}} \frac{1}{u'_a} \\
&= \left( (1 - \mu)(1 - \alpha) \frac{1}{\omega_R M_P \frac{c'}{Y}} \frac{l'}{n'} \right)^{\frac{1}{x}} \\
&= \left( (1 - \mu)(1 - \alpha) \frac{1}{\omega_R M_P \frac{c'}{Y}} \frac{1}{1 - u'} \right)^{\frac{1}{x}}. \tag{C.17}
\end{aligned}$$

## Other Variables

Goods production is from (B.21) given by

$$\begin{aligned}
Y &= k^{\mu} (n^{\alpha} n'^{1 - \alpha})^{1 - \mu} \\
Y^{\frac{1}{1 - \mu}} &= k^{\frac{\mu}{1 - \mu}} n^{\alpha} n'^{1 - \alpha} \\
Y &= \left( \frac{k}{Y} \right)^{\frac{\mu}{1 - \mu}} n^{\alpha} n'^{1 - \alpha}. \tag{C.18}
\end{aligned}$$

Labor substitution is determined by (B.28) and (B.29),

$$[(1 - mi)\kappa e_W^\psi - \psi]w = \frac{(1 - \theta_W)(1 - \beta\theta_W)}{\theta_W(1 + e_W\varphi)} \frac{1}{e_W^2}, \quad (\text{C.19})$$

$$[(1 - mi')\kappa e_W'^\psi - \psi]w' = \frac{(1 - \theta_W)(1 - \beta'\theta_W)}{\theta_W(1 + e_W'\varphi)} \frac{1}{e_W'^2}. \quad (\text{C.20})$$

Housing production is from (B.22) and (B.26) given by

$$\begin{aligned} I_H &= v^\nu \\ &= (\nu q I_H)^\nu \\ &= \left( \nu Y \frac{q I_H}{Y} \right)^\nu. \end{aligned} \quad (\text{C.21})$$

The real house price is derived by substituting (C.11) and (C.18) into the identity

$$q = \frac{q I_H}{Y} \frac{Y}{I_H}. \quad (\text{C.22})$$

Intermediate housing input is now from (C.7) determined by the identity

$$v = \nu q I_{H,t}. \quad (\text{C.23})$$

Nonresidential capital is now determined by the identity

$$k = \frac{k}{Y} Y. \quad (\text{C.24})$$

Goods consumption is now determined by the identities

$$c = \frac{c}{Y} Y, \quad (\text{C.25})$$

$$c' = \frac{c'}{Y} Y. \quad (\text{C.26})$$

Housing consumption is now determined by the identities

$$h = \frac{q h c}{c q}, \quad (\text{C.27})$$

$$h' = \frac{q h' c'}{c' q}. \quad (\text{C.28})$$



The real wages are from (B.24) and (B.25) given by

$$w = (1 - \mu)\alpha \frac{Y}{M_P n}, \quad (\text{C.29})$$

$$w' = (1 - \mu)(1 - \alpha) \frac{Y}{M_P n'}. \quad (\text{C.30})$$

Labor supply is from (B.5) and (B.17) given by

$$l = [u_c w (1 - u)]^{\frac{1}{\varphi}}, \quad (\text{C.31})$$

$$l' = [u'_c w' (1 - u')]^{\frac{1}{\varphi}}. \quad (\text{C.32})$$

The internal migration rate of workers who anticipate unemployment are from (B.6) and (B.18) given by

$$m_u = \left[ \frac{u_c w l}{\omega_R} \right]^{\frac{1}{\chi}} \frac{1}{u_a}, \quad (\text{C.33})$$

$$m'_u = \left[ \frac{u'_c w' l'}{\omega_R} \right]^{\frac{1}{\chi}} \frac{1}{u'_a}. \quad (\text{C.34})$$

## D Appendix: Data

The sample covers the U.S. economy in 1987Q1-2016Q4, at a quarterly frequency. (D.1)-(D.10) are retrieved from the database of the U.S. Federal Reserve Bank of St. Louis. (D.11) is retrieved from the Annual Social and Economic Supplement ("the March supplement") of the Current Population Survey. The time series are constructed as described below.

$$\text{Gross domestic product p.c.: } \frac{PCEC_t + PNFI_t + PRFI_t + GCE_t}{GDPDEF_t \cdot CNP16OV_t}. \quad (\text{D.1})$$

$$\text{Personal consumption expenditures p.c.: } \frac{PCEC_t}{DPCERD3Q086SBEA_t \cdot CNP16OV_t}. \quad (\text{D.2})$$

$$\text{Nonresidential investment p.c.: } \frac{PNFI_t}{A008RD3Q086SBEA_t \cdot CNP16OV_t}. \quad (\text{D.3})$$

$$\text{Home mortgage loan liabilities p.c.: } \frac{HHMSDODNS_t}{GDPDEF_t \cdot CNP16OV_t}. \quad (\text{D.4})$$

$$\text{House prices: } \frac{CSUSHPISA_t}{GDPDEF_t}. \quad (\text{D.5})$$

$$\text{Effective federal funds rate: } \frac{FEDFUNDS_t}{4 \cdot 100}. \quad (\text{D.6})$$

$$\text{Price inflation: } GDPDEF_t. \quad (\text{D.7})$$

$$\text{Wage inflation: } AHETPI_t. \quad (\text{D.8})$$

$$\text{Employment rate: } \frac{EMRATIO_t}{100}. \quad (\text{D.9})$$

$$\text{Unemployment rate: } \frac{UNRATE_t}{100}. \quad (\text{D.10})$$

$$\text{Cross-county migration rate: } \frac{MIGRATIONRATE_t}{100}. \quad (\text{D.11})$$

(D.1)-(D.5) are normalized relative to 1987Q1, then log-transformed, and lastly detrended by series-specific linear trends. (D.7)-(D.8) are log-differenced. (D.11) is quartered and interpolated to a quarterly frequency using Denton's (1971) method. Finally, (D.6)-(D.11) are demeaned. These transformations are applied to make the data consistent with its theoretical counterparts.

The text codes in (D.1)-(D.10) are the codes applied by the U.S. Federal Reserve Bank of St. Louis. The text codes in (D.1)-(D.11) abbreviate:

- PCEC: Personal consumption expenditures (billions of dollars, SA at annual rate, quarterly frequency).
- PNFI: Gross private domestic fixed nonresidential investment (billions of dollars, SA at annual rate, quarterly frequency).
- PRFI: Gross private domestic fixed residential investment (billions of dollars, SA at annual rate, quarterly frequency).
- GCE: Government consumption expenditures and gross investment (billions of dollars, SA at annual rate, quarterly frequency).
- GDPDEF: Gross domestic product: Implicit price deflator (index, SA, quarterly frequency).
- CNP16OV: Civilian noninstitutional population (thousands of persons, NSA, quarterly frequency).
- DPCERD3Q086SBEA: Personal consumption expenditures: Implicit price deflator (index, SA, quarterly frequency).
- A008RD3Q086SBEA: Gross private domestic investment: Fixed investment: Non-residential: Implicit price deflator (index, SA, quarterly frequency).
- HHMSDODNS: Home mortgages: Liability: Households and nonprofit organizations: Level (billions of dollars, SA, quarterly frequency).
- CSUSHPISA: S&P Case-Shiller U.S. National Home Price Index (index, SA, quarterly frequency).
- FEDFUNDS: Effective federal funds rate (pct., NSA, quarterly frequency).
- AHETPI: Average hourly earnings of production and nonsupervisory employees: Total private (dollars per hour, SA, quarterly frequency).
- EMRATIO: Civilian employment-population ratio (pct., SA, quarterly frequency).
- UNRATE: Civilian unemployment rate (pct., SA, quarterly frequency).
- MIGRATIONRATE: The geographical mobility rate by tenure of owners: Different house in the United States: Different county, total (pct., annual frequency).





## Chapter 3

# Mortgage Defaults, Bank Runs, and Regulation in a Housing Economy

**By:** Marcus Mølbak Ingholt, Johannes Poeschl, and Xue Zhang\*

We develop a macroeconomic model capturing the linkages between house price fluctuations, mortgage defaults, and bank runs. In the model, endogenous house price drops can lead to bank runs if losses on mortgage lending push the liquidation value of the banking sector below the value of the sector's outstanding deposits. Once a series of technology shocks is simulated for the model to match output, the model predicts the historical movements in key real and financial variables in the U.S. Moreover, bank runs are ruled out during the mid-2000s boom and attain a high probability during the Savings and Loan Crisis and the Great Recession. We use the model to evaluate different macroprudential policies. Stricter loan-to-value standards and bank capital requirements reduce the frequency of bank panics, but at the cost of impeding financial intermediation over the business cycle. A dynamic capital requirement is contrarily able to both curb systemic risk and support intermediation, as this tightening only binds in times of financial distress.

*JEL classification:* D58, E32, E44, G21.

*Keywords:* House prices. Mortgage defaults. Bank runs. Macroprudential regulation. Global solutions to DSGE models.

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# 1 Introduction

Between 2007 and 2010, the U.S. economy witnessed a financial crisis unprecedented in recent history. Falling house prices initially caused mortgage delinquency and default rates to spike and banks to incur losses on mortgage lending. The associated depletion of capital forced banks to contract lending and raise lending rates. This amplified the fall in house prices, further weakening the banks' financial positions to a point that triggered runs on a variety of institutions, such as Bear Stearns in March 2008 and Lehman Brothers in September 2008. The ensuing fire sales of bank assets amplified the overall distress in financial markets, as well as the contraction in economic activity.<sup>1</sup>

Despite these events, macroeconomic models remain silent about the linkages between house price fluctuations, mortgage defaults, and bank runs.<sup>2</sup> This gap largely stems from the literature diverging on how to model the effects of the housing boom-bust cycle on real activity. One strand of the literature relies on financial accelerator effects. In these models, weak balance sheet conditions of firms or households undermine their access to credit, creating a negative feedback loop that impairs their balance sheets further (Bernanke and Gertler, 1989; Kiyotaki and Moore, 1997).<sup>3</sup> Another strand of the literature studies bank runs on corporate financing markets, where banks intermediate funds from households to nonfinancial firms. This literature emphasizes either how liquidity mismatch in banking opens up the possibility of bank runs (Diamond and Dybvig, 1983) or how the depletion of bank capital in economic downturns hinders banks' abilities to intermediate funds (Gertler and Kiyotaki, 2010).<sup>4</sup> Since mortgage credit is paramount to the workings of the modern macroeconomy, linkages between housing markets and bank runs raise some fundamental questions. How do house price busts lead to bank runs? Through which channels do house prices affect financial intermediation outside bank runs? What, if any, role does the state of the economy play in the probability of bank runs occurring? Can macroprudential regulation eliminate the risk of bank runs?

In order to understand these issues better, we develop a dynamic stochastic general equilibrium (DSGE) model with patient and impatient households, a housing market, and a banking sector. Our model exhibits three key features: mortgage loans that are collateralized by houses, endogenous defaults on mortgage loans, and endogenous bank runs. We solve the model globally, by approximating the nonlinear policy and transition functions on a sparse state grid and computing the resulting equilibrium via backward

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<sup>1</sup>See Gertler and Gilchrist (2018) for an overall description of financial factors in the Great Recession.

<sup>2</sup>A few papers do model defaults on mortgage loans. Ferrante (2019) studies the linkages between financial shocks, defaultable long-term mortgage loans, risk premia, and the real economy. Moreover, Clerc, Derviz, Mendicino, Moyen, Nikolov, Stracca, Suarez, and Vardoulakis (2015) study mortgage defaults in a setting where banks lend to both households and firms. Neither of these contributions model bank runs.

<sup>3</sup>Other papers studying price constraints include Bernanke, Gertler, and Gilchrist (1999), Gourio (2012), Brunnermeier and Sannikov (2014), and He and Krishnamurthy (2012, 2013). Other papers studying quantity constraints include Iacoviello (2005), Iacoviello and Neri (2010), Mendoza (2010), Jermann and Quadrini (2012), and Liu et al. (2013).

<sup>4</sup>See also, e.g., Gertler and Kiyotaki (2015) and Gertler, Kiyotaki, and Prestipino (2016, 2017).

iteration (Brumm and Scheidegger, 2017). Within this framework, a fall in house prices leads to bank runs for the following reasons. House price drops lower the market value of indebted households' houses, inducing an increasing share of the households to default on their mortgage loan obligations. As mortgage default rates spike and the repossession values of houses fall, banks increasingly incur losses on lending, which erodes their net worth. If the banks' net worth falls sufficiently so that the liquidation value of the banking sector is smaller than the value of the sector's outstanding deposits, bank runs from the depositors can occur, as a sunspot equilibrium.

As in reality, the mortgage market is disciplined by two occasionally binding regulatory constraints. On the banks' side, lending is restricted by a leverage constraint, limiting banks' lending ability to a multiple of their net worth. On the households' side, borrowing is restricted by a collateral constraint. Whether the lending constraint or the collateral constraint binds depends on the state of the economy, and therefore varies over time. Importantly, in the absence of bank runs, there is a financial accelerator channel leading from house prices to credit, independently of which constraint that binds. If the leverage constraint binds, house price drops reduce the banks' lending ability, by eroding their net worth. Reversely, if the collateral constraint binds, house price drops restrain the impatient homeowners' borrowing ability. In either case, the contraction in intermediation causes homeowners to cut back on their consumption and housing expenditures, thereby further amplifying the housing crisis and making bank runs more likely.

We calibrate a series of technology shocks such that the model matches the path of output in the U.S. during the period 1985-2018. Given these shocks, the model explains most of the cyclical variation in untargeted variables, such as consumption, house prices, mortgage credit, the bank credit spread, household net worth, and the mortgage default rate. Thus, the housing-financial cycle can, within our framework, largely be accounted for by technology shocks. Importantly, both in the simulation and the data, the mortgage default rate, the bank credit spread, and the probability of bank runs are high during the Savings and Loan Crisis and the Great Recession. This is a result of house prices being low in these episodes, making the default option more attractive to borrowers. Savers respond to the elevated risk by demanding higher risk premia on their deposits, consequently increasing the bank credit spread. This contrasts with the end-1990s and mid-2000s expansion, where the model predicts the default rate to be low, as booming house prices discouraged borrowers from defaulting. In particular, in 2005-2006, defaults become so rare that bank runs are completely ruled out. Within one year, however, this expectation is overturned, leading the bank run probability to reach its historical peak. The simulation thus captures the rapid transition from a low-risk environment to a high-risk environment at the onset of the Financial Crisis. For most of the sample period, mortgage credit moves in tandem with house prices, as the collateral constraint is binding. However, during the 2000-2004 period, soaring house prices slacken the collateral constraint, prompting the lending constraint to bind. In this way, the simulation nests two leading theories about



the business cycle in the early-2000s, namely that collateral constraints on households were slack (Guerrieri and Iacoviello, 2017) and that mortgage credit issuance was supply determined (Justiniano et al., 2018).

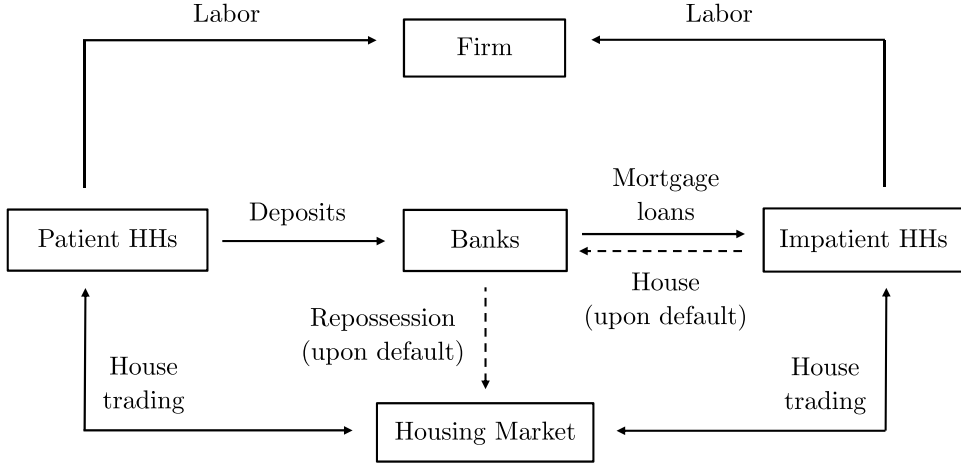
We lastly employ the model to examine the effectiveness of three macroprudential policies in reducing the frequency and severity of financial crises. The policies are (i) a lower loan-to-value limit, (ii) a higher minimum bank capital requirement, and (iii) a dynamic capital requirement that requires banks to provision against expected lending losses by setting funds aside. Higher loan-to-value limits and static capital requirements forcefully reduce mortgage default rates and the probability of bank runs, by necessitating the households to increasingly rely on equity financing, making them less prone to defaulting. However, this comes at the cost of impeding financial intermediation over the business cycle. Provisioning against expected lending losses is, by contrast, able to improve financial stability and, at the same time, increase financial intermediation. The policy does so by requiring banks to contract lending only in times where their expected losses are high, allowing them to intermediate more if the lending conditions are sound.

The rest of the chapter is structured as follows. Section 2 presents the theoretical model. Section 3 lays out the calibration of the model. Section 4 demonstrates model dynamics historically and as impulse responses. Section 5 conducts the macroprudential experiments. Section 6 contains the concluding remarks.

## 2 Model

The model has an infinite time horizon. Time is discrete, and indexed by  $t$ . The economy is populated by two representative groups of households: a patient group and an impatient group. Households consume goods and housing services, and supply labor inelastically. There is no direct financial market between the patient and impatient households. Banks instead specialize in intermediating funds between the two groups of households. The time preference heterogeneity implies that, in and close to the steady state, the patient households make deposits in the banks, which then issue mortgage loans to the impatient households. The impatient households may default on their mortgage payments, in which case their houses are repossessed by the banks. If such defaults cause the liquidation value of the banking sector to fall below the value of the sector's outstanding deposits, banks may experience runs by depositors, in which case they default on their deposits. Goods are produced by a representative firm, combining employment and nonresidential capital. The patient households own and operate the banks and the firm. We denote variables and parameters related to the patient households with a "P", the impatient households with an "I", and the banks with a "B". Figure 1 provides an overview of the economy. The equilibrium conditions are derived in Appendix A.

**Figure 1: OVERVIEW OF THE ECONOMY IN EQUILIBRIUM**



## 2.1 Patient and Impatient Households

The economic size of each group of households is measured by its wage share:  $\mu \in (0, 1)$  for the patient households and  $1 - \mu$  for the impatient households. Each group is comprised of a unit continuum of individual households. The aggregate households maximize their respective utility functions,

$$\mathbb{E}_0 \left\{ \sum_{t=0}^{\infty} (\beta^J)^t \left[ \chi^J \frac{(C_t^J)^{1-\sigma} - 1}{1-\sigma} + (1 - \chi^J) \frac{(H_t^J)^{1-\sigma} - 1}{1-\sigma} \right] \right\}, \quad (1)$$

where  $J \in \{P, I\}$ . Moreover,  $C_t^J$  denotes goods consumption, and  $H_t^J$  are housing services derived from a portfolio of houses held in the beginning of period  $t$ . Finally,  $\beta^J \in (0, 1)$  measures the pure time discount factor,  $\chi^J \in (0, 1)$  measures the consumption weight in the utility function, and  $\sigma \in \mathbb{R}_+$  is the coefficient of relative risk aversion of the households. The household types differ along two dimensions. First,  $\beta^P > \beta^I$ , so that the impatient households discount future utility more than the patient households do. Second,  $\chi^P > \chi^I$ , so that the impatient households have a higher preference for housing than the patient households have. This latter heterogeneity ensures that the share of houses which are owned by the impatient households is equal to the share of households which are net-borrowers.

**Houses** The housing portfolio of each household consists of houses that are owned by the individual household members:

$$H_t^J = \int_i H_{i,t}^J di, \quad (2)$$

where  $J \in \{P, I\}$  and  $H_{i,t}^J$  denotes the house that is owned by household member  $i$  in the beginning of period  $t$ . The idiosyncratic real price of house  $i$ ,  $P_{i,t}^H$ , is the product of an

idiosyncratic house price shock and an aggregate house price:

$$P_{i,t}^H = \varepsilon_{i,t} P_t^H, \quad (3)$$

where  $\varepsilon_{i,t} \sim \text{Lognormal}(-\frac{1}{2}(\nu^\varepsilon)^2, \nu^\varepsilon)$  is the idiosyncratic house price shock, and  $P_t^H$  denotes the aggregate real house price. The idiosyncratic house price distribution implies that  $\mathbb{E}_{t-1}\{P_{i,t}^H\} = \mathbb{E}_{t-1}\{P_t^H\}$ . Housing transactions occur in the following way. By the end of period  $t$ , the households sell their remaining housing stock,  $(1 - \delta)H_t^J$ , off at price  $P_t^H$ , and purchase a new stock,  $H_{t+1}^J$ , also at price  $P_t^H$ . The net change in the value of the housing portfolio from period  $t$  to period  $t + 1$  is consequently

$$[H_{t+1}^J - (1 - \delta)H_t^J] P_t^H, \quad (4)$$

where  $\delta \in [0, 1]$  measures the depreciation of residential capital. The net change in the value of the housing portfolio must be financed on the period  $t$  budget of the households.

**Bank Deposits** Patient households lend in the form of single-period bonds,  $D_{t+1}^P$ , that are held by banks from period  $t$  to period  $t + 1$ . We think of this debt as comprising both deposit and market financing, where neither source of finance is covered by deposit insurance. The bonds promise to pay a non-contingent gross interest rate,  $R_{t+1}^D$ , in period  $t + 1$ . If there is *no bank run* in period  $t + 1$ , the patient households will receive the full promised return on their deposits. If there is a *bank run*, by contrast, the patient households will only receive a gross return,  $X_{t+1}^D R_{t+1}^D$ , where  $X_{t+1}^D$  denotes the recovery rate of deposits.

**Mortgage Loans** The banks issue an aggregate portfolio of single-period mortgage loans to the impatient households,

$$M_{t+1}^J = \int_i M_{i,t+1}^J di, \quad (5)$$

where  $J \in \{I, B\}$  and  $M_{i,t+1}^J$  denotes the mortgage loan that is issued to household member  $i$  in period  $t$ . The loan issued to member  $i$  is secured by the house owned by member  $i$ .

The individual impatient household may choose to default on its mortgage loan. If a household member *does not default* in period  $t$ , the household has to pay a debt service,  $R_t^M M_{i,t}^I$ , to the bank, where  $R_t^M$  denotes the gross interest rate on the mortgage loan. If the household member reversely *does default*, the bank repossesses the member's house, and sells it off, in order to make up for the loss on the loan. Loans are nonrecourse, so the bank cannot seek the deficiency balance from the borrower elsewhere if the proceeds from selling the house are insufficient to cover the losses. These assumptions together imply that the aggregate impatient household has the following mortgage-related net expenses

on their period  $t$  budget:

$$[1 - \Phi_t^M(1 - X_t^M)] R_t^M M_t^I - M_{t+1}^I, \quad (6)$$

where  $\Phi_t^M$  denotes the mortgage default rate across all household members, and  $X_t^M$  denotes the recovery rate across all household members. The *realized* gross return rate on mortgage loans is

$$\tilde{R}_t^M \equiv [1 - \Phi_t^M(1 - X_t^M)] R_t^M. \quad (7)$$

This rate captures that the realized return on mortgage loans differs from the mortgage rate, because of default losses.

The individual impatient household is forced to give up the current value of its housing stock,  $(1 - \delta)P_{i,t}H_{i,t}^I$ , to the bank if the household defaults on its mortgage loan. The recovery rate of a defaulted mortgage loan  $i$  is thereby

$$X_{i,t}^M \equiv \frac{(1 - \delta)P_{i,t}H_{i,t}^I}{R_t^M M_{i,t}^I}. \quad (8)$$

In turn, the recovery rate across all members of the impatient household is

$$X_t^M = \int_{X_{i,t}^M \leq 1} X_{i,t}^M f(X_{i,t}^M) dX_{i,t}^M, \quad (9)$$

where  $f(X_{i,t}^M)$  denotes the probability density function of  $X_{i,t}^M$ .

**Collateral Constraint** Because each loan is secured by a corresponding house, utility maximization of the aggregate impatient household is subject to an occasionally binding collateral constraint,

$$M_{t+1}^I \leq \kappa P_t^H H_{t+1}^I, \quad (10)$$

where  $\kappa \in [0, 1]$  measures the loan-to-value limit. The collateral constraint importantly ties the borrowing ability of the impatient households to their housing wealth.

**Optimal Default Decision** The individual household chooses to default if and only if the home value that it foregoes,  $(1 - \delta)P_{i,t}H_{i,t}^I$ , is less than the outstanding liability,  $R_t^M M_{i,t}^I$ , that the household owes to the bank:

$$(1 - \delta)P_{i,t}H_{i,t}^I \leq R_t^M M_{i,t}^I. \quad (11)$$

The impatient households thus default on their mortgage loans whenever the idiosyncratic recovery rate of the defaulted loan falls below unity (i.e.,  $X_{i,t}^M \leq 1$ ).

The aggregate mortgage default rate can be characterized by a cutoff rule for the idiosyncratic house price shock. The cutoff rule is given by

$$(1 - \delta)\bar{\varepsilon}_t P_t^H H_t^I = R_t^M M_t^I, \quad (12)$$

where  $\bar{\varepsilon}_t$  denotes the cutoff value of the idiosyncratic house price shock. If the realized idiosyncratic house price shock falls below the cutoff value (i.e.,  $\varepsilon_{i,t} \leq \bar{\varepsilon}_t$ ), it is optimal for the individual household  $i$  to default on its mortgage loan. The aggregate mortgage default rate is therefore

$$\Phi_t^M = \Pr(\varepsilon_{i,t} \leq \bar{\varepsilon}_t). \quad (13)$$

Defaults and foreclosures occur in the beginning of each period, while repossessions first occur at the end of the period. This timing captures that foreclosures usually are a time-consuming processes which allow the affected homeowners to remain in their houses until the repossession.<sup>5</sup> In our model, foreclosed households buy new houses from the banks at the end of each period, financed by loans and incomes obtained during the period. As such, the households never become homeless.

**Budget Constraints** Utility maximization of the patient households is subject to a budget constraint,

$$\begin{aligned} C_t^P + [H_{t+1}^P - (1 - \delta)H_t^P] P_t^H + D_{t+1}^P + S_{t+1}^P + \frac{n_t^P}{\mu} \\ = W_t L_t^P + [1 - \Phi_t^D(1 - X_t^D)] R_t^D D_t^P + R_t^S S_t^P + (1 - \tau)(\Pi_t^B + \Pi_t^F), \end{aligned} \quad (14)$$

where  $S_{t+1}^P$  denotes a risk-free single-period government bond,  $R_t^S$  denotes the gross interest rate on government bonds,  $n_t^P$  denotes equity invested into new banks,  $W_t$  denotes the real wage of both households,  $L_t^P$  denotes employment of patient workers measured in hours,  $\Phi_t^D$  denotes the aggregate default rate of deposits,  $X_t^D$  denotes the aggregate recovery rate of deposits,  $\Pi_t^B$  denotes dividends from the banking sector, and  $\Pi_t^F$  denotes dividends from the firm. Finally,  $\tau \in [0, 1]$  measures capital income taxation. The aggregate default rate of deposits is zero in the absence of bank runs (i.e.,  $\Phi_t^D = 0$ ), since we are considering a representative risk-sharing banking sector.

Utility maximization of the impatient households is subject to a budget constraint,

$$C_t^I + [H_{t+1}^I - (1 - \delta)H_t^I] P_t^H + [1 - \Phi_t^M(1 - X_t^M)] R_t^M M_t^I = W_t L_t^I + M_{t+1}^I + T_t^I, \quad (15)$$

where  $L_t^I$  denotes employment of impatient workers measured in hours, and  $T_t^I$  denotes

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<sup>5</sup>The average length of a foreclosure has not been less than a quarter since measurements of foreclosure timelines began in 2007 ([ATTOM Data Solutions, 2019](#)).

transfers from the government. The government runs a balanced budget in every period, and redistributes capital income taxes to the impatient households:

$$T_t^I = \tau (\Pi_t^B + \Pi_t^F). \quad (16)$$

Because the government runs a balanced budget, the government bond is in zero net supply in every period (i.e.,  $S_{t+1}^P = 0$ ).

**Credit Spreads** We define the household credit spread as the difference between the interest rate on mortgage loans ( $R_{t+1}^M$ ) and the interest rate on deposits ( $R_{t+1}^D$ ). We additionally define the bank credit spread as the difference between the interest rate on deposits ( $R_{t+1}^D$ ) and the interest rate on government bonds ( $R_{t+1}^S$ ). The interest rate on deposits is determined by the first-order condition of the patient households with respect to deposits:

$$R_{t+1}^D = \frac{\mathbf{U}_1^P(C_t^P, H_t^P)}{\beta^P \mathbb{E}_t \{ \mathbf{U}_1^P(C_{t+1}^P, H_{t+1}^P) [1 - \Phi_{t+1}^D (1 - X_{t+1}^D)] \}}, \quad (17)$$

where  $\mathbf{U}_1^P(C_t^P, H_t^P)$  denotes the marginal utility of goods consumption for the patient household. The deposit rate is comprised of both a compensation for saving instead of consuming and a risk premium compensating for the possibility that banks might default. The interest rate on government bonds is determined by the first-order condition of the patient households with respect to government bonds:

$$R_{t+1}^S = \frac{\mathbf{U}_1^P(C_t^P, H_t^P)}{\beta^P \mathbb{E}_t \{ \mathbf{U}_1^P(C_{t+1}^P, H_{t+1}^P) \}}. \quad (18)$$

The bank credit spread accordingly captures the risk premium on deposits.

## 2.2 Banks

The banking sector is comprised of a unit continuum of individual banks. The sector maximizes the aggregate discounted value of its current and expected future dividend payouts to its owners,

$$\mathbb{E}_0 \left\{ \sum_{t=0}^{\infty} (\beta^P)^t (1 - \eta)^{t-1} \frac{\mathbf{U}_1^P(C_t^P, H_t^P)}{\mathbf{U}_1^P(C_0^P, H_0^P)} \Pi_t^B \right\}, \quad (19)$$

where  $(\beta^P)^t \frac{\mathbf{U}_1^P(C_t^P, H_t^P)}{\mathbf{U}_1^P(C_0^P, H_0^P)}$  denotes the stochastic discount factor of the patient households, and  $\eta \in [0, 1]$  measures the bank exit rate. The banks discount future dividends at the stochastic discount factor of the patient households, since these households own and operate the banks. We assume that a fixed share of the banks exit the economy in every period, following, e.g., [Gertler and Kiyotaki \(2010, 2015\)](#). Dividend payouts are constituted by

the net worth of the exiting banks being paid out:

$$\Pi_t^B = \eta n_t^B, \quad (20)$$

where  $n_t^B$  denotes the net worth of the incumbent banks in the beginning of period  $t$ . This assumption ensures that banks do not accumulate equity infinitely, which would otherwise allow the banks to outsave their leverage constraint, implying that they would no longer need to take deposits in order to issue loans. New banks enter at the same rate as the old banks exit, keeping the aggregate number of banks constant.

The banking sector is comprised of newly entering banks and incumbent banks. The net worth of the banking sector is

$$N_t^B = n_t^P + (1 - \eta)n_t^B, \quad (21)$$

where  $N_t^B$  denotes the net worth of the banking sector. In the beginning of each period, the patient households finance the entry of new banks by investing equity ( $n_t^P$ ) into the banking sector. New banks have the following net worth:

$$n_t^P = \eta \mathcal{E}, \quad (22)$$

where  $\mathcal{E} \in \mathbb{R}_+$  measures the gross amount of equity invested into the new banks. The net worth of the incumbent banks is

$$n_t^B = \tilde{R}_t^M M_t^B - R_t^D D_t^B. \quad (23)$$

It follows from (21) and (23) that the net worth of the banking sector becomes negative if the realized return on mortgage lending falls to the extent that this return and the newly invested equity do not cover the deposit liabilities.

**Balance Sheet Constraint** Mortgage loans are the only assets of the banks, while deposits and equity are their only liabilities. The balance sheet constraint of the banks consequently requires that

$$M_{t+1}^B = D_{t+1}^B + N_t^B. \quad (24)$$

**Leverage Constraint** Regulators impose an occasionally binding leverage constraint on the banks,

$$\frac{M_{t+1}^B}{N_t^B} \leq \psi, \quad (25)$$

where  $\psi \geq 0$  is the leverage limit. The leverage constraint can be motivated on the grounds of microprudential reasons, e.g., to limit the incentive misalignment between shareholders

and depositors (Diamond and Rajan, 2000). Furthermore, leverage constraints are a crucial part of the Basel regulatory framework (Basel Committee on Banking Supervision, 1988, 2004, 2010). The leverage limit is the inverse of the minimum capital requirement. The leverage constraint importantly ties the lending ability of the banks to their net worth. The banks maximize dividends subject to this constraint.

## Bank Runs

We model bank runs as coordination failures of the patient households and banks to roll over the deposits previously kept within the banking system, as in Calvo (1998), Cole and Kehoe (2000), and Gertler and Kiyotaki (2015). We denote all bank variables pertaining to a bank-run state with a \*. Once a bank run happens, the entire banking sector defaults on all of its liabilities, implying that the default rate of deposits reaches unity (i.e.,  $\Phi_t^{D*} = 1$ ). The assets of the banks are liquidated (i.e.,  $N_t^{B*} = 0$ ), and the banks can no longer take deposits or grant mortgage loans (i.e.,  $D_{t+1}^{B*} = M_{t+1}^{B*} = 0$ ). The patient households receive the liquidation value. The recovery rate of deposits for the patient households is

$$X_t^{D*} \equiv \frac{\tilde{R}_t^{M*} M_t^B}{R_t^D D_t^B}. \quad (26)$$

In a bank run, all impatient households stop paying their mortgage loans, causing the mortgage default rate to reach unity (i.e.,  $\Phi_t^{M*} = 1$ ). The impatient households' houses are foreclosed and repossessed by the banks, just like with defaulters' houses in the no-run states of the economy. The realized gross return rate on mortgage loans in the bank-run period is

$$\tilde{R}_t^{M*} = \frac{1 - \mu}{\mu} [1 - 1 \cdot (1 - X_t^M)] R_t^M = \frac{1 - \mu}{\mu} X_t^M R_t^M. \quad (27)$$

The impatient households buy new houses from the banks at the end of the bank-run period, again just like defaulters do in the no-run states. However, during bank runs, the banks can only resell the houses at  $\frac{1-\mu}{\mu}$  pct. of the value that they would have been able to sell the houses for outside bank runs. For  $\mu > \frac{1}{2}$ , this discount during bank runs captures that – because it is the entire housing stock of the impatient households that is resold – a fire sale occurs.

**Bank-Run Condition** The conditions for the existence and materialization of bank runs follow the conditions in Gertler and Kiyotaki (2015). A bank-run equilibrium exists if the liquidation value of the banking sector falls below the value of the sector's outstanding deposits. The net worth of the banking sector will in that case be negative in the event of a run. This implies that, if the run happens, the patient households cannot fully recover their deposits by liquidating the bank assets. Given the definition of the recovery rate of



deposits in (26), a bank run *can* occur whenever

$$X_t^{D^*} < 1. \quad (28)$$

If a bank-run equilibrium exists, a sunspot will decide whether the patient households and banks fail to coordinate their actions in order to avoid the run. The probability that they fail, implying that the run *materializes*, is

$$\pi_t^{NR \rightarrow R} = 1 - \min(X_t^{D^*}, 1). \quad (29)$$

In this way, the less the patient households recover from their deposits in the case of a bank run, the more likely it is that the run will actually occur.

**Transition Matrix** The economy will transition back to a no-run state probabilistically after a bank run, once the banks reenter the economy. The transition matrix between the different states of the economy is

$$\pi_t = \begin{pmatrix} 1 - \pi_t^{NR \rightarrow R} & \pi_t^{NR \rightarrow R} \\ 1 - \pi_t^{R \rightarrow R} & \pi_t^{R \rightarrow R} \end{pmatrix},$$

where  $\pi_t^{R \rightarrow R} \in (0, 1)$  measures the bank-run persistence.

## 2.3 Production

The representative firm produces goods, which can be consumed or invested into housing, by hiring labor from both households. The profits to be maximized are

$$\Pi_t^F = Y_t - W_t (L_t^P + L_t^I), \quad (30)$$

subject to the available goods production technology,

$$Y_t = Z_t \mathcal{K}^{1-\alpha} (L_t^P + L_t^I)^\alpha, \quad (31)$$

where  $Y_t$  denotes goods production,  $Z_t$  is an aggregate technology shock, and  $\mathcal{K} \in \mathbb{R}_+$  measures a fixed aggregate stock of nonresidential capital. The firm owns and operates the nonresidential capital stock. Moreover,  $\alpha \in (0, 1)$  measures the goods production elasticity with respect to labor. The technology shock follows an AR(1) process,

$$\log Z_t = \rho^Z \log Z_{t-1} + \varepsilon_t^Z, \quad (32)$$

where  $\varepsilon_t^Z \sim N(0, \nu^Z)$ .

## 2.4 Equilibrium

### Market Clearing

The model contains a goods market, a housing market, a deposit market, a mortgage loan market, a government bond market, and two labor markets.

**Market Clearing in No-Run States** All markets are active in the no-run states of the economy. The market clearing conditions are

$$Y_t = \mu C_t^P + (1 - \mu)C_t^I + \delta P_t^H \mathcal{H}, \quad (33)$$

$$\mathcal{H} = \mu H_{t+1}^P + (1 - \mu)H_{t+1}^I, \quad (34)$$

$$D_{t+1}^B = \mu D_{t+1}^P, \quad (35)$$

$$M_{t+1}^B = (1 - \mu)M_{t+1}^I, \quad (36)$$

$$\mu S_{t+1}^P = 0, \quad (37)$$

$$L_t^P = \mu \mathcal{L}^P, \quad (38)$$

$$L_t^I = (1 - \mu)\mathcal{L}^I, \quad (39)$$

where  $\mathcal{H} \in \mathbb{R}_+$  measures the fixed aggregate stock of housing, and  $\mathcal{L}^P \in \mathbb{R}_+$  and  $\mathcal{L}^I \in \mathbb{R}_+$  measure the inelastic labor supplies from the patient and impatient households. Housing investments replenish the housing stock as it depreciates, keeping the stock constant.

**Market Clearing in Bank-Run States** All banks get liquidated in the bank-run states of the economy, and there are thus no deposit or mortgage loan markets in these states. The goods, housing, and government bond markets clear just as in the no-run states, while the labor market clearing conditions change. The market clearing conditions are

$$Y_t = \mu C_t^P + (1 - \mu)C_t^I + \delta P_t^H \mathcal{H}, \quad (40)$$

$$\mathcal{H} = \mu H_{t+1}^P + (1 - \mu)H_{t+1}^I, \quad (41)$$

$$\mu S_{t+1}^P = 0, \quad (42)$$

$$L_t^P = (1 - \xi)\mu \mathcal{L}^P, \quad (43)$$

$$L_t^I = (1 - \xi)(1 - \mu)\mathcal{L}^I, \quad (44)$$

where  $\xi \in [0, 1]$  measures the employment loss during bank runs. This employment loss captures that firms are forced to reduce employment when financial markets break down, due to working capital requirements. The importance of working capital requirements in explaining output contractions has been emphasized by, e.g., [Neumeyer and Perri \(2005\)](#) and [Mendoza and Yue \(2012\)](#).

### 3 Solution and Calibration of the Model

Since the model contains nonlinearities stemming from the occasionally binding constraints, equilibrium multiplicity, and endogenous time-varying risk, we solve it with a global solution method. More precisely, we approximate the nonlinear policy and transition functions on a sparse state grid, and compute the resulting equilibrium via backward iteration, as in [Brumm and Scheidegger \(2017\)](#). The expectations are computed over Gauss-Hermite quadrature nodes for normally distributed variables and Gauss-Legendre quadrature nodes for bounded variables. Appendix [B](#) charts the solution algorithm. Appendices [C-D](#) additionally present the equation systems for the no-run and run states of the economy and for the steady state.

The model is calibrated to match the U.S. economy during the period 1985-2018, at a quarterly frequency. Table [1](#) reports the chosen parameter values. One set of parameters which is standard in the literature, we set to the conventional values or normalize, without further motivating these values. For the remaining non-standard set of parameters, we motivate the values below. Information on the data we use is provided in Appendix [E](#).

We begin by describing the parameters relating to the household sector. We select the discount factor of the patient households ( $\beta^P = 0.9948$ ) so that the net deposit rate in the steady state matches the real quarterly 12-month London Interbank Offered Rate based on U.S. dollars (0.52 pct.). The consumption utility weight for the patient households ( $\chi^P = 0.922$ ) is set for the ratio of residential investments to consumption in the steady state ( $\frac{\delta P^H \mathcal{H}}{\mu C^P + (1-\mu) C^I}$ ) to match the corresponding ratio in the data (6.5 pct.). The share of patient households ( $\mu = 0.60$ ) ensures that 40 pct. of the households are impatient, while the consumption utility weight for the impatient households ( $\chi^I = 0.788$ ) ensures that 40 pct. of the houses are owned and used as collateral by the impatient households. These values are in keeping with estimates by [Iacoviello \(2005\)](#) and [Iacoviello and Neri \(2010\)](#), and furthermore approximately match the empirical share of households with loan-to-value ratios above 80 pct. (33 pct.). This cross-restriction between the two parameters follows from the model assumption in Subsection [2.1](#) that every loan is secured by a corresponding house. The coefficient of relative risk aversion ( $\sigma = 2.00$ ) is identical to the value that, e.g., [Kaplan et al. \(2017\)](#) use. The volatility of the idiosyncratic house price shock ( $\nu^\varepsilon = 0.18$ ) implies that the mortgage default rate in the steady state is equal to the ratio of nonperforming loans that are past due 90+ days to total loans in the data (2.3 pct.).

We next describe the parameters relating to the banks. We choose the endowment of newly entering banks ( $\mathcal{E} = 0.09$ ) for the ratio of bank net profits to consumption in the steady state ( $\frac{\eta(n^B - \mathcal{E})}{\mu C^P + (1-\mu) C^I}$ ) to be equal to the ratio of net dividends from commercial banks to consumption in the data (0.9 pct.). The bank exit rate ( $\eta = 0.10$ ) is set so that the ratio of bank net profits to mortgage credit in the steady state ( $\frac{\eta(n^B - \mathcal{E})}{M^B}$ ) matches the ratio of net dividends from commercial banks to outstanding mortgage loans in the data (0.3 pct.). The leverage limit ( $\psi = 1/0.08 = 12.5$ ) follows the total capital requirement

**Table 1:** PARAMETER VALUES

Description		Value
<b>Households</b>		
Share of patient households	$\mu$	0.60
Discount factor, patient households	$\beta^P$	0.9948
Discount factor, impatient households*	$\beta^I$	0.9900
Consumption weight, patient households	$\chi^P$	0.922
Consumption weight, impatient households	$\chi^I$	0.788
Coefficient of relative risk aversion	$\sigma$	2.00
Standard deviation, idiosyncratic house price shock	$\nu^\varepsilon$	0.18
Depreciation rate of housing stock*	$\delta$	0.01
Loan-to-value limit*	$\kappa$	0.80
<b>Banks</b>		
Endowment of new banks	$\mathcal{E}$	0.09
Bank exit rate	$\eta$	0.10
Leverage limit	$\psi$	1/0.08
Bank-run persistence	$\pi^{R \rightarrow R}$	12/13
<b>Production and Redistribution</b>		
Nonresidential capital stock <sup>†</sup>	$\mathcal{K}$	1.00
Employment, patient and impatient households <sup>†</sup>	$\mathcal{L}^P, \mathcal{L}^I$	1.00
Labor share of output*	$\alpha$	0.60
Capital income tax rate	$\tau$	0.20
Employment loss during bank runs	$\xi$	0.109
Stock of housing <sup>†</sup>	$\mathcal{H}$	1.00
<b>Aggregate Technology Shock Process</b>		
Autocorrelation	$\rho^Z$	0.9688
Standard deviation <sup>†</sup>	$\nu^Z$	0.01

\*Standard value. <sup>†</sup>Normalization.

imposed under Basel I-III regulation (Basel Committee on Banking Supervision, 1988, 2004, 2010). The bank-run persistence rate ( $\pi^{R \rightarrow R} = 12/13$ ) implies an average duration of bank runs of 3.25 years in the model, consistent with the average length of financial crises in OECD countries, according to Laeven and Valencia's (2013) database.

We finally describe the parameters relating to production, redistribution, and the aggregate shock process. The capital income tax rate ( $\tau = 0.20$ ) is close to the average capital tax rates that Leeper, Plante, and Traum (2010) and Sims and Wolff (2018) compute. The employment loss during bank runs ( $\xi = 0.109$ ) matches the drop in aggregate weekly hours per capita that occurred from 2007Q2 to 2009Q4. The autocorrelation of technology shocks ( $\rho^Z = 0.9688$ ) is identical to the autocorrelation of total labor productivity detrended by a log-linear trend.

## 4 Model Dynamics

We now use the model to assess the linkages between business cycle fluctuations, mortgage defaults, and bank runs. We first illustrate how a large exogenous drop in output, such as the one experienced by the U.S. economy during the Great Recession, may lead to elevated levels of mortgage defaults and potentially also bank runs. We then examine the historical contribution of technology shocks to the housing-financial cycle.

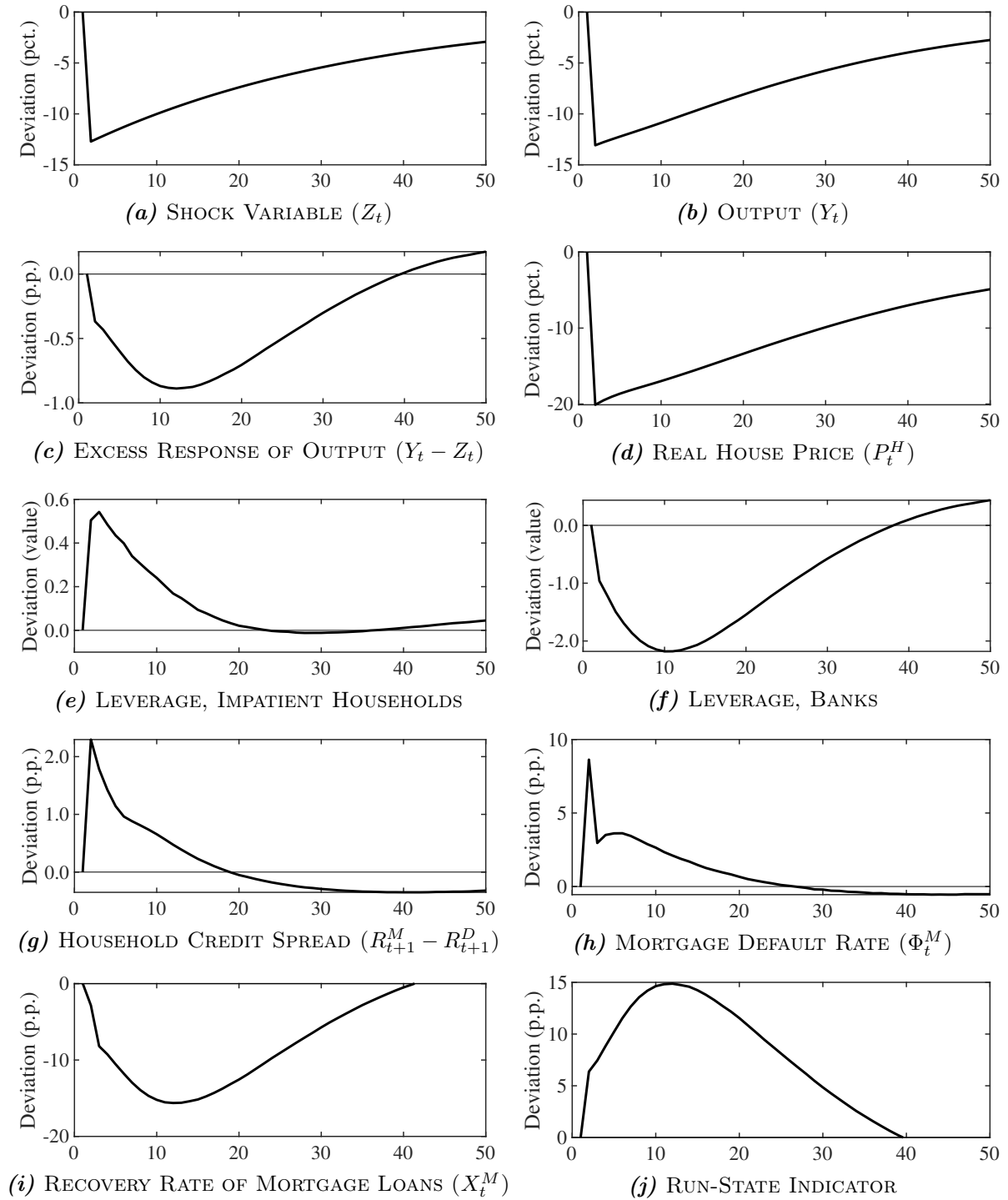
### 4.1 Impulse Responses

Figure 2 plots the generalized impulse responses to a negative technology shock which lowers total factor productivity by 13.6 pct. The size of this shock is consistent with the drop in the detrended real sum of consumption and residential investments from 2005Q2 to 2009Q2. Because the impulse response to a given shock depends on the initial state of the economy, we report the generalized impulse responses, simulated over 500,000 economies. The generalized impulse responses can be interpreted as the average responses across the state space of the model.

The negative technology shock reduces the labor incomes of both households by *at least* 13.6 pct. in all simulated economies. This causes the households to cut spending on consumption and housing services, leading house prices to fall by around 20 pct. The shock is propagated into the financial sector via two channels. The income losses lead the patient households to supply fewer deposits and, if the collateral constraint is slack, the impatient households to demand more mortgage loans. At the same time, the lower value of homes results in higher default rates, as the default option is made more attractive to the borrowers, as well as in lower liquidation values of repossessed homes. In consequence, both the deposit rate and the mortgage rate rise. However, the mortgage rate rises by more than the deposit rate, so that the household credit spread widens, reflecting that the risk premium on mortgage loans is higher. The associated losses on mortgage lending erode the banks' net worth, tightening their leverage constraints. Banks issue fewer loans in all economies, because either the collateral constraint or the leverage constraint is tightened.

Bank runs start occurring in some of the economies in which the losses on mortgage lending push the liquidation value of the banking sector below the value of the sector's outstanding deposits. Thus, about 15 pct. of the economies are in a bank-run state three years after the initial innovation. The runs generate an employment loss, due to the working capital requirement, causing output to drop by  $13.6/(1 - 0.109) = 15.3$  pct. in these economies. Because of this excess drop in output, average output falls by more than the initial reduction in technology, as shown in Figure 2c. Banks are, on average, less levered. This is an average effect of economies with bank runs, in which the leverage ratio falls to zero, and economies without bank runs, in which bank leverage increases, due to bank net worth falling by more than bank assets.

**Figure 2:** IMPULSE RESPONSES TO A NEGATIVE TECHNOLOGY SHOCK

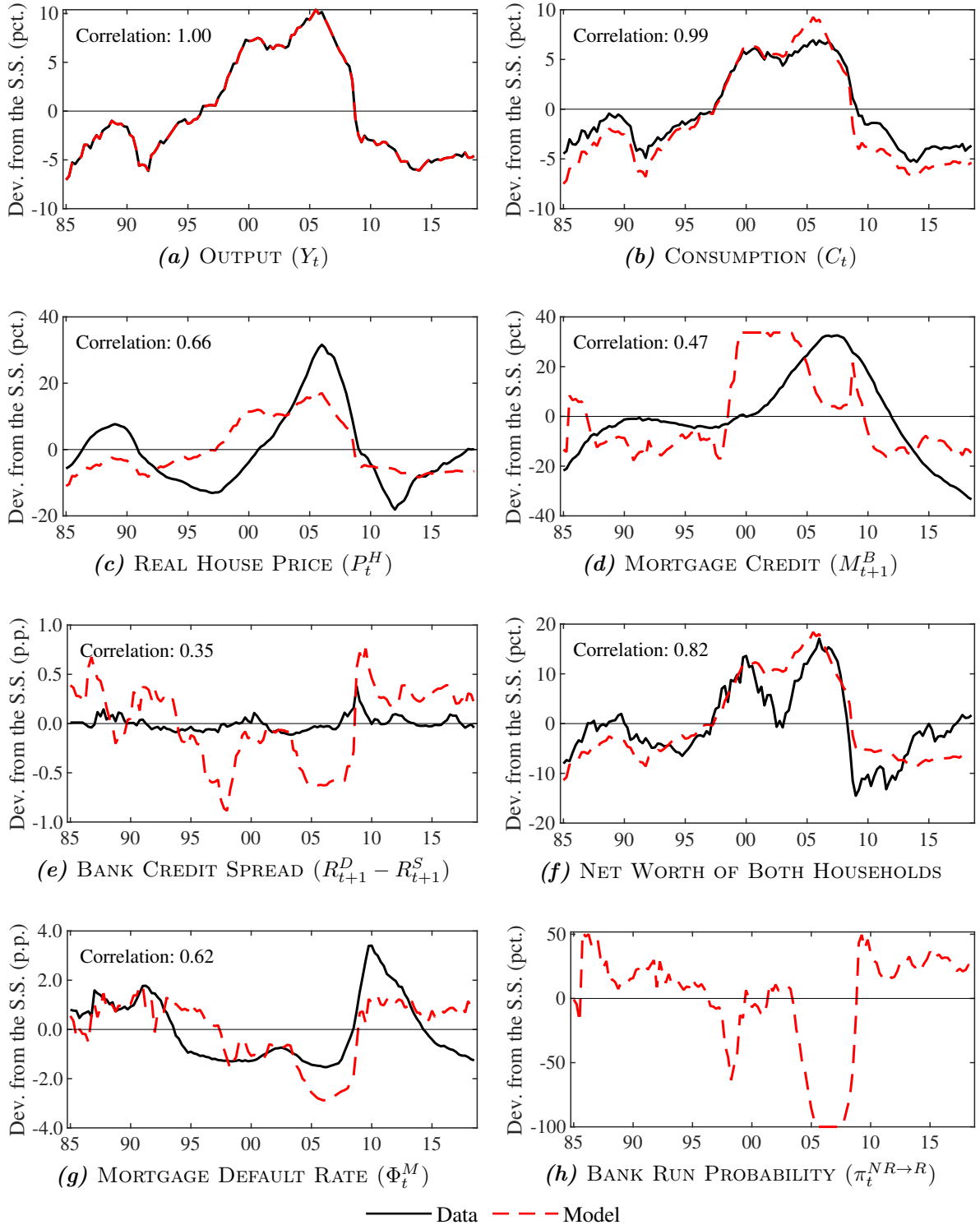


*Note:* We simulate 500,000 economies for 1,100 periods, then shock each economy with an additional negative shock in period 1,010, and finally compute the average deviation that is caused by this shock.

## 4.2 Matching Aggregate Dynamics

We now calibrate a series of technology shocks such that the model matches the path of detrended output across the period 1985-2018. This exercise allows us both to evaluate the

**Figure 3: HISTORICAL PATHS OF EMPIRICAL AND THEORETICAL VARIABLES**



*Note:* The sunspot condition for bank runs is set so that bank runs ex post never occur.

explanatory power of the model and to shed light on the contribution of technology shocks to the housing-financial cycle. In the simulation, we set the sunspot condition in (29) so that bank runs ex post never occur. This assumption is meant to capture that agents may ex ante anticipate the possibility of bank runs, but unexpected government intervention

ex post ensures that nationwide systemic bank runs never take place, consistent with developments during the Financial Crisis. Figure 3 plots the associated theoretical and empirical paths of output, consumption, house prices, mortgage credit, the bank credit spread, household net worth, the mortgage default rate, and the probability of bank runs. Figure 3 also reports the correlation between the theoretical and empirical series. Information on data sources is provided in Appendix E.

By construction, the model perfectly matches the historical path of output. A crucial success of the model is that it reasonably precisely explains the cyclical variation in key housing-financial variables, along with consumption, using only the technology shock. Importantly, both in the simulation and the data, the mortgage default rate, the bank credit spread, and the probability of bank runs are high during the Savings and Loan Crisis in the late-1980s and during the Great Recession. This is a result of house prices being low in these episodes, making the default option more attractive to borrowers. Savers respond to the elevated risk by demanding higher risk premia on their deposits, consequently increasing the bank credit spread between deposits and risk-free bonds. The prediction of a high probability of bank runs during the Savings and Loan Crisis is highly realistic. For instance, out of 3,234 thrift institutions in 1986, 1,043 institutions were closed due to losses on mortgage lending before the end of 1995, according to [Curry and Shibut \(2000\)](#). Zooming in on the end-1990s and mid-2000s expansion, the model predicts the default rate to be low, again consistent with the data, as booming house prices discouraged borrowers from defaulting. In particular, in 2005-2006, defaults become so rare that bank runs are completely ruled out. Within one year, however, this expectation is overturned, leading the bank run probability to reach its historical peak. In this way, the simulation captures the rapid transition from a low-risk environment to a high-risk environment at the onset of the Financial Crisis.

The realistic effects of technology shocks on financial intermediation in the model largely stem from the effects on house prices and mortgage credit. In both the simulation and the data, house prices and mortgage credit start out slightly below their steady-state levels, and increase from the mid-1990s until around 2005, after which they plummet. House prices are themselves driven by labor-income-induced shifts to households' housing demand. For most of the sample period, mortgage credit moves in tandem with house prices, as the collateral constraint is binding. However, during the 2000-2004 period, soaring house prices slacken the collateral constraint, prompting the lending constraint to bind. In this way, the simulation nests two leading theories about the business cycle in the early-2000s, namely that collateral constraints on households were slack ([Guerrieri and Iacoviello, 2017](#)) and that mortgage credit issuance was supply determined ([Justiniano et al., 2018](#)).



## 5 Macprudential Regulation

In this section, we compare the effects of three macroprudential interventions:

1. Lowering the loan-to-value limit on mortgage borrowing.
2. Increasing the minimum capital requirement on mortgage lending.
3. Imposing a dynamic capital requirement on mortgage lending.

We simulate the model under each policy, and report the results in Table 2.

**Lower Loan-to-Value Limit** Column 3 of Table 2 reports the effects of lowering the loan-to-value limit by a quarter, from 80 pct. to 60 pct. Household leverage levels are naturally lower, as the collateral constraint is more restrictive. Since households are less levered, they are less prone to defaulting on their mortgage loans. Default rates and household credit spreads accordingly fall. Bank runs are completely eliminated, as the banks are less exposed to house price fluctuations. Thus, the financial system is more stable. However, financial variables, such as leverage, deposits, mortgage credit, and credit spreads, also become more correlated with output, since the collateral constraint binds more often. In this way, financial acceleration is – within a more limited scope – accentuated. Another adverse effect of instituting the lower loan-to-value limit is that this impedes financial intermediation over the business cycle. This is visible from the levels of deposits and mortgage loans, which are, on average, lower.

**Higher Bank Capital Requirement** Column 4 of Table 2 reports the effects of lowering the leverage limit by a quarter, from 12.5 to 9.375. Correspondingly, the minimum capital requirement rises to 10.67 pct., from 8 pct. Financial intermediation is again curbed, only this time because the leverage constraint is more restrictive. Besides this, because banks intermediate less, household and bank leverage ratios are lower, reducing the probability that creditors will not recover their assets. Thus, the financial system is again more stable, as exemplified by lower default rates and bank run probabilities. For a given reduction in intermediation, the higher capital requirement is less effective at curbing systemic financial risk, as compared to the lower loan-to-value limit. This is evident from comparing the size of the reduction in default rates or bank run probabilities with the size of the reduction in intermediation under the two interventions. The disparity is due to the households' default decision being closely related to the household leverage ratio, implying that the loan-to-value policy affects the default decision more directly than the capital requirement policy. Notwithstanding this, an advantage of the higher capital requirement is that this policy does not increase the correlation of financial variables with output to the same extent as the loan-to-value policy did. This is because the capital requirement ties credit to bank net worth, which moves less than one-for-one with house prices. The LTV constraint contrarily ties credit to housing values, which moves one-for-one with house prices.

**Table 2:** DESCRIPTIVE STATISTICS UNDER DIFFERENT MACROPRUDENTIAL REGIMES

	Baseline	$\kappa = 0.6$	$\psi = 9.375$	$\gamma = 1$
<b>Consumption and House Prices</b>				
Avg. consumption, pt. hh. (level)	2.89	2.85	2.96	2.88
Avg. consumption, impt. hh. (level)	2.04	2.14	2.02	2.06
Std. dev. of house price (pct.)	8.52	7.36	7.38	8.24
Std. dev. of consumption, pt. hh. (pct.)	6.89	4.35	3.95	5.51
Std. dev. of consumption, impt. hh. (pct.)	19.61	2.78	9.84	16.40
<b>Financial Variables</b>				
Leverage, impt. hh. (level)	2.43	2.30	2.32	2.49
Leverage, banks (level)	12.08	11.09	9.34	11.82
Deposits (level)	1.43	1.38	1.32	1.46
Mortgage loans (level)	1.56	1.51	1.48	1.60
Household credit spread (pct. per year)	1.96	1.36	2.01	1.83
Mortgage default rate (pct.)	1.07	0.18	0.39	0.90
Mortgage recovery rate (pct.)	95.11	96.79	96.51	95.10
Bank runs (per 100 years)	5.00	0.00	0.41	3.89
<b>Correlations between Financial Variables and Output</b>				
Leverage, impt. hh.	-0.20	-0.94	-0.60	-0.26
Leverage, banks	0.00	0.70	0.17	0.17
Deposits	0.16	0.72	0.08	0.24
Mortgage loans	0.16	0.71	0.07	0.22
Household credit spread	-0.06	-0.59	0.02	-0.06
Mortgage default rate	-0.15	-0.66	-0.30	-0.17
Mortgage recovery rate	0.09	0.85	0.32	0.10

*Note:* The baseline model is calibrated to the following values:  $\kappa = 0.80$ ,  $\psi = 12.5$ , and  $\gamma = 0$ . We simulate 10,000 economies for 20,000 periods under each policy regime, then discard the first 10,000 periods, and finally compute averages over the 10,000 economies. We discard the bank-run states of the economy when computing descriptive statistics for the financial variables, since these variables are not defined in the bank-run states.

**Imposing a Dynamic Capital Requirement** We finally introduce a dynamic capital requirement that requires banks to provision against expected lending losses by setting funds aside. More specifically, we let the leverage limit in (25) respond negatively to the expected future lending losses:

$$\psi_t = \bar{\psi} - \gamma \mathbb{E}_t \{ \Phi_{t+1}^M (1 - X_{t+1}^M) \}, \quad (45)$$

where  $\bar{\psi} \geq 0$  now measures the static leverage limit, and  $\gamma \geq 0$  measures the degree of loan loss provisioning. Column 5 of Table 2 reports the effects of keeping the static leverage limit at 12.5 but, at the same time, imposing a dynamic capital requirement, with  $\gamma = 1$ . The dynamic requirement is able both to substantially reduce systemic financial risk and to increase financial intermediation, unlike the two former policies. The dynamic requirement does so by, on the one hand, requiring banks to extend fewer loans when their

expected future lending losses are high. This substantially reduces household leverage in these episodes, discouraging the households from defaulting. On the other hand, the dynamic requirement also allows banks to extend more loans when lending conditions are sound. This prompts household and bank leverage ratios, along with intermediation, to be higher than under the baseline calibration. Thus, with this policy, the regulator can better fine-tune the trade-off between financial prudence and intermediation.

## 6 Concluding Remarks

We develop a macroeconomic model capturing the linkages between house price fluctuations, mortgage defaults, and bank runs. In the model, endogenous house price drops can lead to bank runs if the liquidation value of the banking sector falls below the value of the sector's outstanding deposits. We show that the model explains the historical movements in key housing-financial variables, with a technology shock as the only source of exogenous variation. We then employ the model to evaluate different macroprudential policies. Stricter loan-to-value standards and bank capital requirements forcefully curb systemic risk, but at the cost of impeding financial intermediation over the business cycle. A dynamic capital requirement is contrarily able to both curb systemic risk and support intermediation, as this tightening only binds in times of financial distress. In ongoing work, we further explore the welfare consequences of these different macroprudential policies.

# A Appendix: Dynamic Equilibrium Conditions

## Patient Households

The aggregate patient household maximizes its utility function,

$$\max_{\{C_t^P, H_{t+1}^P, D_{t+1}^P, S_{t+1}^P\}_{t=0}^{\infty}} \mathbb{E}_0 \left\{ \sum_{t=0}^{\infty} (\beta^P)^t \mathbf{U}^P(C_t^P, H_t^P) \right\}, \quad (\text{A.1})$$

subject to a budget constraint,

$$\begin{aligned} C_t^P + [H_{t+1}^P - (1 - \delta)H_t^P] P_t^H + D_{t+1}^P + S_{t+1}^P + \frac{n_t^P}{\mu} \\ = W_t L_t^P + [1 - \Phi_t^D(1 - X_t^D)] R_t^D D_t^P + R_t^S S_t^P + (1 - \tau) (\Pi_t^B + \Pi_t^F). \end{aligned} \quad (\text{A.2})$$

The aggregate patient household maximizes its utility function with respect to goods consumption, housing, bank deposits, and government bonds. The resulting first-order conditions are

$$\mathbf{U}_1^P(C_t^P, H_t^P) = \lambda_t^P, \quad (\text{A.3})$$

$$\lambda_t^P P_t^H = \beta^P \mathbb{E}_t \{ (1 - \delta) \lambda_{t+1}^P P_{t+1}^H + \mathbf{U}_2^P(C_{t+1}^P, H_{t+1}^P) \}, \quad (\text{A.4})$$

$$\lambda_t^P = \beta^P \mathbb{E}_t \{ \lambda_{t+1}^P [1 - \Phi_{t+1}^D(1 - X_{t+1}^D)] R_{t+1}^D \}, \quad (\text{A.5})$$

$$\lambda_t^P = \beta^P \mathbb{E}_t \{ \lambda_{t+1}^P R_{t+1}^S \}, \quad (\text{A.6})$$

where  $\lambda_t^P$  denotes the Lagrange multiplier on (A.2).

## Impatient Households

The aggregate impatient household maximizes its utility function,

$$\max_{\{C_t^I, H_{t+1}^I, M_{t+1}^I\}_{t=0}^{\infty}} \mathbb{E}_0 \left\{ \sum_{t=0}^{\infty} (\beta^I)^t \mathbf{U}^I(C_t^I, H_t^I) \right\}, \quad (\text{A.7})$$

subject to a budget constraint,

$$C_t^I + [H_{t+1}^I - (1 - \delta)H_t^I] P_t^H + [1 - \Phi_t^M(1 - X_t^M)] R_t^M M_t^I = W_t L_t^I + M_{t+1}^I + T_t^I, \quad (\text{A.8})$$

and to an occasionally binding collateral constraint,

$$M_{t+1}^I \leq \kappa P_t^H H_{t+1}^I. \quad (\text{A.9})$$

The aggregate impatient household maximizes its utility function with respect to goods consumption, housing, and mortgage loans. The resulting first-order conditions are

$$\mathbf{U}_1^I(C_t^I, H_t^I) = \lambda_t^I, \quad (\text{A.10})$$

$$\lambda_t^I P_t^H = \beta^I \mathbb{E}_t \{ (1 - \delta) \lambda_{t+1}^I P_{t+1}^H + \mathbf{U}_2^I(C_{t+1}^I, H_{t+1}^I) \} + \lambda_t^{CC} \kappa P_t^H, \quad (\text{A.11})$$

$$\lambda_t^I = \lambda_t^{CC} + \beta^I \mathbb{E}_t \{ \lambda_{t+1}^I [1 - \Phi_{t+1}^M(1 - X_{t+1}^M)] R_{t+1}^M \}, \quad (\text{A.12})$$

where  $\lambda_t^I$  denotes the Lagrange multiplier on (A.8), and  $\lambda_t^{CC}$  denotes the Lagrange multiplier on (A.9).

## Banks

The banking sector maximizes the aggregate discounted value of its current and expected future dividend payouts to its owners,

$$\max_{\{M_{t+1}^B, D_{t+1}^B\}_{t=0}^{\infty}} \mathbb{E}_0 \left\{ \sum_{t=0}^{\infty} (\beta^P)^t (1-\eta)^{t-1} \frac{\mathbf{U}_1^P(C_t^P, H_t^P)}{\mathbf{U}_1^P(C_0^P, H_0^P)} \Pi_t^B \right\}, \quad (\text{A.13})$$

subject to the profit pay-out function,

$$\Pi_t^B = \eta n_t^B, \quad (\text{A.14})$$

to the law-of-motion for the net worth of the incumbent banks,

$$n_t^B = \tilde{R}_t^M M_t^B - R_t^D D_t^B, \quad (\text{A.15})$$

to the balance sheet constraint,

$$M_{t+1}^B = D_{t+1}^B + N_t^B, \quad (\text{A.16})$$

and to the bank capital requirement constraint,

$$\frac{M_{t+1}^B}{N_t^B} \leq \psi. \quad (\text{A.17})$$

The associated Lagrange function after substitution with (A.14)-(A.16) is

$$\max_{\{M_{t+1}^B, D_{t+1}^B\}_{t=0}^{\infty}} \mathbb{E}_0 \left\{ \sum_{t=0}^{\infty} \Lambda_t \left[ \eta \left( \tilde{R}_t^M M_t^B - R_t^D D_t^B \right) + \lambda_t^{LC} \left[ \psi \left( M_{t+1}^B - D_{t+1}^B \right) - M_{t+1}^B \right] \right] \right\},$$

where  $\Lambda_t \equiv (\beta^P)^t (1-\eta)^{t-1} \frac{\mathbf{U}_1^P(C_t^P, H_t^P)}{\mathbf{U}_1^P(C_0^P, H_0^P)}$  and  $\lambda_t^{LC}$  denotes the Lagrange multiplier on (A.17).

The banking sector maximizes its dividend payouts with respect to bank deposits and mortgage loans. The resulting first-order conditions are

$$\eta \mathbb{E}_t \left\{ \Lambda_{t+1} \tilde{R}_{t+1}^M \right\} + \psi \lambda_t^{LC} - \lambda_t^{LC} = 0, \quad (\text{A.18})$$

$$\eta \mathbb{E}_t \left\{ \Lambda_{t+1} R_{t+1}^D \right\} + \psi \lambda_t^{LC} = 0. \quad (\text{A.19})$$

These first-order conditions can be combined to give

$$\eta \mathbb{E}_t \left\{ \Lambda_{t+1} \left( \tilde{R}_{t+1}^M - R_{t+1}^D \right) \right\} = \lambda_t^{LC}. \quad (\text{A.20})$$

## Production

The firm maximizes its profits,

$$\max_{\{L_t^P, L_t^I\}_{t=0}^{\infty}} \Pi_t^F = Y_t - W_t(L_t^P + L_t^I), \quad (\text{A.21})$$

subject to the goods production technology,

$$Y_t = Z_t \mathcal{K}^{1-\alpha} (L_t^P + L_t^I)^\alpha. \quad (\text{A.22})$$

The firm maximizes its profits with respect to employment from the patient households and employment from the impatient households. The resulting first-order condition for both types of employment is

$$W_t = \alpha \frac{Y_t}{L_t^P + L_t^I}. \quad (\text{A.23})$$

## B Appendix: Numerical Solution Algorithm

We chart our solution algorithm below. The algorithm is similar to the one in [Brumm and Scheidegger \(2017\)](#).

**State Space** Collect the states in  $\mathcal{S} \equiv (N^P, N^B, Z, \aleph)$ , where  $\aleph$  is a sunspot shock taking the values 0 and 1. Furthermore, collect the exogenous states in  $\mathcal{Y} \equiv (Z, \aleph)$ .

**Unknown Functions** We need to determine the following ten objects as functions of the current and future exogenous states:

- Four nonlinear policy functions for the consumption of both households, house prices, and the value function of the banks:  $\mathbf{C}^P(\mathcal{S})$ ,  $\mathbf{C}^I(\mathcal{S})$ ,  $\mathbf{P}^H(\mathcal{S})$ , and  $\bar{\mathbf{V}}(\mathcal{S})$ .
- Two laws-of-motion for the net worth of the patient households and banks:  $\mathbf{N}^{P'}(\mathcal{S}, \mathcal{Y}')$  and  $\mathbf{N}^{B'}(\mathcal{S}, \mathcal{Y}')$ .
- Default and recovery rates of deposits:  $\Phi^{D'}(\mathcal{S}, \mathcal{Y}')$  and  $\mathbf{X}^{D'}(\mathcal{S}, \mathcal{Y}')$ .
- Default and recovery rates of mortgage loans:  $\Phi^{M'}(\mathcal{S}, \mathcal{Y}')$  and  $\mathbf{X}^{M'}(\mathcal{S}, \mathcal{Y}')$ .

**Solution Algorithm** We approximate the unknown functions on a state space, and solve the model by backward iteration. An outline of the algorithm is follows below:

1. **Compute the steady state of the model.**
2. **Construct a grid:** We use a sparse grid.
  - (a) Bounds:
    - Exogenous processes: +/- 4 unconditional standard deviations.
    - Endogenous processes: around the steady state.
  - (b) Grid level: 7, meaning that we use seven nested sets of basis functions.
3. **Initial guess:** We use the steady-state values of the policy and transition functions.
4. **Expectations:** At iteration  $i$ , given some policy functions,  $\mathbf{C}_i^P(\mathcal{S})$ ,  $\mathbf{C}_i^I(\mathcal{S})$ ,  $\mathbf{P}_i^H(\mathcal{S})$ , and  $\bar{\mathbf{V}}_i(\mathcal{S})$ , and laws-of-motion,  $\mathbf{N}_i^{P'}(\mathcal{S}, \mathcal{Y}')$  and  $\mathbf{N}_i^{B'}(\mathcal{S}, \mathcal{Y}')$ , compute

$$\mathbf{C}_i^{P'}(\mathcal{S}, \mathcal{Y}') = \mathbf{C}_i^P(\mathbf{N}_i^{P'}(\mathcal{S}, \mathcal{Y}'), \mathbf{N}_i^{B'}(\mathcal{S}, \mathcal{Y}'), \mathcal{Y}'),$$

and so on. After having done this, expectations are computed as integrals over  $\mathcal{Y}'$ .

5. **Compute the new policy functions:** Solve a system of nonlinear equations in order to find the policy functions,  $\mathbf{C}_{i+1}^P(\mathcal{S})$ ,  $\mathbf{C}_{i+1}^I(\mathcal{S})$ ,  $\mathbf{H}_{i+1}^{P'}(\mathcal{S})$ ,  $\mathbf{H}_{i+1}^{B'}(\mathcal{S})$ , and  $\mathbf{P}_{i+1}^H(\mathcal{S})$ , and laws-of-motion,  $\mathbf{N}_{i+1}^{P'}(\mathcal{S}, \mathcal{Y}')$  and  $\mathbf{N}_{i+1}^{B'}(\mathcal{S}, \mathcal{Y}')$ , in the no-run and run equilibria.
6. **Update** unknown functions, interest rates, and laws-of-motion.
7. **Check convergence:** Compute errors as

$$\epsilon^{C^P} = \|\mathbf{C}_{i+1}^P(\mathcal{S}) - \mathbf{C}_i^P(\mathcal{S})\|_\infty,$$

and so on. If  $\epsilon^{C^P} > 10^{-5}$ , go to iteration  $i + 1$  and repeat from step 4 onward, and otherwise stop.



## C Appendix: Equation Systems

### No-Run Equation System

#### Patient Households

Variables to be determined:  $H^{P'}$ ,  $D^{P'}$ ,  $R^{S'}$ ,  $C^P$ , and  $\tilde{R}^D$ .

$$\begin{aligned} \mathbf{U}_1^P(C^P, H^P)P^H &= \beta^P \mathbb{E} \left\{ (1 - \delta) \mathbf{U}_1^P(C^{P'}, H^{P'})P^{H'} + \mathbf{U}_2^P(C^{P'}, H^{P'}) \right\}, \\ \mathbf{U}_1^P(C^P, H^P) &= \beta^P \mathbb{E} \left\{ \mathbf{U}_1^P(C^{P'}, H^{P'}) \tilde{R}^{D'} \right\}, \\ \mathbf{U}_1^P(C^P, H^P) &= \beta^P \mathbb{E} \left\{ \mathbf{U}_1^P(C^{P'}, H^{P'}) R^{S'} \right\}, \\ C^P + [H^{P'} - (1 - \delta)H^P] P^H + D^{P'} + \frac{n^P}{\mu} &= WL^P + \tilde{R}^D D^P + (1 - \tau) (\Pi^B + \Pi^F), \\ \tilde{R}^D &= [1 - \Phi^D(1 - X^D)] R^D. \end{aligned}$$

#### Impatient Households

Variables to be determined:  $H^{I'}$ ,  $M^{I'}$ ,  $\lambda^{CC}$ ,  $\Phi^M$ ,  $X^M$ , and  $\tilde{R}^M$ .

$$\begin{aligned} \mathbf{U}_1^I(C^I, H^I) P^H &= \beta^I \mathbb{E} \left\{ (1 - \delta) \mathbf{U}_1^I(C^{I'}, H^{I'}) P^{H'} + \mathbf{U}_2^I(C^{I'}, H^{I'}) \right\} + \lambda^{CC} \kappa P^H, \\ \mathbf{U}_1^I(C^I, H^I) &= \lambda^{CC} + \beta^I \mathbb{E} \left\{ \mathbf{U}_1^I(C^{I'}, H^{I'}) \tilde{R}^{M'} \right\}, \\ M^{I'} &= \kappa P^H H^I \quad \text{if the collateral constraint binds, and} \\ \lambda^{CC} &= 0 \quad \text{if the collateral constraint is slack,} \\ \Phi^M &= \Pr(\varepsilon_i \leq \bar{\varepsilon}), \\ X^M &= \int_{X_i^M \leq 1} X_i^M f(X_i^M) dX_i^M, \\ \tilde{R}^M &\equiv [1 - \Phi^M(1 - X^M)] R^M. \end{aligned}$$

## Banks

Variables to be determined:  $M^{B'}$ ,  $N^B$ ,  $n^P$ ,  $n^B$ ,  $\lambda^{LC}$ ,  $D^{B'}$ ,  $\Phi^D$ ,  $X^D$ , and  $\Pi^B$ .

$$\begin{aligned}
M^{B'} &= D^{B'} + N^B, \\
N^B &= n^P + (1 - \eta)n^B, \\
n^P &= \eta\mathcal{E}, \\
n^B &= \tilde{R}^M M^B - R^D D^B, \\
\eta\mathbb{E} \left\{ \Lambda' \left( \tilde{R}^{M'} - R^{D'} \right) \right\} &= \lambda^{LC}, \\
M^{B'} &= \psi N^{B'} \quad \text{if the leverage constraint binds, and} \\
\lambda^{LC} &= 0 \quad \text{if the leverage constraint is slack,} \\
\Phi^D &= 0, \\
X^D &= 1, \\
\Pi^B &= \eta n^B.
\end{aligned}$$

## Production

Variables to be determined:  $Y$ ,  $W$ , and  $\Pi^F$ .

$$\begin{aligned}
Y &= Z\mathcal{K}^{1-\alpha} (L^P + L^I)^\alpha, \\
W &= \alpha \frac{Y}{L^P + L^I}, \\
\Pi^F &= Y - W (L^P + L^I).
\end{aligned}$$

## Market Clearing

Variables to be determined:  $C^I$ ,  $P^H$ ,  $R^{D'}$ ,  $R^{M'}$ ,  $S^{P'}$ ,  $L^P$ , and  $L^I$ .

$$\begin{aligned}
Y &= \mu C^P + (1 - \mu)C^I + \delta P^H \mathcal{H}, \\
\mathcal{H} &= \mu H^{P'} + (1 - \mu)H^{I'}, \\
D^{B'} &= \mu D^{P'}, \\
M^{B'} &= (1 - \mu)M^{I'}, \\
\mu S^{P'} &= 0, \\
L^P &= \mu \mathcal{L}^P, \\
L^I &= (1 - \mu)\mathcal{L}^I.
\end{aligned}$$

## Run Equation System

### Patient Households

Variables to be determined:  $H^{P'}$ ,  $D^{P'^*}$ ,  $R^{S'}$ ,  $C^P$ , and  $\tilde{R}^{D^*}$ .

$$\begin{aligned} \mathbf{U}_1^P(C^P, H^P)P^H &= \beta^P \mathbb{E} \left\{ (1 - \delta) \mathbf{U}_1^P(C^{P'}, H^{P'})P^{H'} + \mathbf{U}_2^P(C^{P'}, H^{P'}) \right\}, \\ D^{P'^*} &= 0, \\ \mathbf{U}_1^P(C^P, H^P) &= \beta^P \mathbb{E} \left\{ \mathbf{U}_1^P(C^{P'}, H^{P'}) R^{S'} \right\}, \\ C^P + [H^{P'} - (1 - \delta)H^P] P^H + D^{P'^*} + \frac{n^{P^*}}{\mu} &= WL^P + \tilde{R}^{D^*} D^P + (1 - \tau) (\Pi^{B^*} + \Pi^F), \\ \tilde{R}^{D^*} &= [1 - \Phi^{D^*}(1 - X^{D^*})] R^D. \end{aligned}$$

### Impatient Households

Variables to be determined:  $H^{I'}$ ,  $M^{I'^*}$ ,  $\lambda^{CC}$ ,  $\Phi^{M^*}$ ,  $X^{M^*}$ , and  $\tilde{R}^{M^*}$ .

$$\begin{aligned} \mathbf{U}_1^I(C^I, H^I) P^H &= \beta^I \mathbb{E} \left\{ (1 - \delta) \mathbf{U}_1^I(C^{I'}, H^{I'}) P^{H'} + \mathbf{U}_2^I(C^{I'}, H^{I'}) \right\} + \lambda^{CC} \kappa P^H, \\ M^{I'^*} &= 0, \\ \mathbf{U}_1^I(C^I, H^I) &= \lambda^{CC} + \beta^I \mathbb{E} \left\{ \mathbf{U}_1^I(C^{I'}, H^{I'}) \tilde{R}^{M^*} \right\}, \\ \Phi^{M^*} &= 1, \\ X^{M^*} &= \int X_i^M f(X_i^M) dX_i^M, \\ \tilde{R}^{M^*} &= \frac{1 - \mu}{\mu} [1 - \Phi^M(1 - X^{M^*})] R^M. \end{aligned}$$

### Banks

Variables to be determined:  $M^{B'^*}$ ,  $N^{B^*}$ ,  $n^{P^*}$ ,  $n^{B^*}$ ,  $\lambda^{LC^*}$ ,  $D^{B'^*}$ ,  $\Phi^{D^*}$ ,  $X^{D^*}$ , and  $\Pi^{B^*}$ .

$$\begin{aligned} M^{B'^*} &= D^{B'^*} + N^{B^*} = 0, \\ N^{B^*} &= n^{P^*} + (1 - \eta)n^{B^*} = 0, \\ n^{P^*} &= 0, \\ n^{B^*} &= 0, \\ D^{B'^*} &= 0, \\ \lambda^{LC^*} &= 0, \\ \Phi^{D^*} &= 1, \\ X^{D^*} &= \frac{\tilde{R}^{M^*} M^B}{R^D D^B}, \\ \Pi^{B^*} &= \eta n^{B^*} = 0. \end{aligned}$$

## Production

Variables to be determined:  $Y$ ,  $W$ , and  $\Pi^F$ .

$$\begin{aligned} Y &= Z\mathcal{K}^{1-\alpha} (L^P + L^I)^\alpha, \\ W &= \alpha \frac{Y}{L^P + L^I}, \\ \Pi^F &= Y - W (L^P + L^I). \end{aligned}$$

## Market Clearing

Variables to be determined:  $C^I$ ,  $P^H$ ,  $S^{P'}$ ,  $L^P$  and  $L^I$ .

$$\begin{aligned} Y &= \mu C^P + (1 - \mu)C^I + \delta P^H \mathcal{H}, \\ \mathcal{H} &= \mu H^{P'} + (1 - \mu)H^{I'}, \\ \mu S^{P'} &= 0, \\ L^P &= (1 - \xi)\mu \mathcal{L}^P, \\ L^I &= (1 - \xi)(1 - \mu)\mathcal{L}^I. \end{aligned}$$

## D Appendix: Steady-State Computation

This appendix documents the derivation of the steady-state solution of the model. An exact numerical solution can be reached by combining the resulting relations as it is done in the steady-state code. We use the steady-state solution to calibrate the model and to construct the state space for the endogenous processes. The steady-state solution is based on the no-run equilibrium, since we assume that there are no bank runs in the steady state.

### Patient Households

Variables to be determined:  $H^P$ ,  $D^P$ ,  $R^S$ ,  $C^P$ , and  $\tilde{R}^D$ .

$$\begin{aligned}
 P^H &= \beta^P \left[ (1 - \delta)P^H + \frac{1 - \chi^P}{\chi^P} \left( \frac{C^P}{H^P} \right)^\sigma \right], \\
 R^D &= \frac{1}{[1 - \Phi^D(1 - X^D)] \beta^P} = \frac{1}{\beta^P}, \\
 R^S &= \frac{1}{\beta^P}, \\
 C^P + \delta P^H H^P + \frac{n^P}{\mu} &= WL^P + (R^D - 1)D^P + (1 - \tau)(\Pi^B + \Pi^F), \\
 \tilde{R}^D &= [1 - \Phi^D(1 - X^D)] R^D.
 \end{aligned}$$

### Impatient Households

Variables to be determined:  $H^I$ ,  $M^I$ ,  $\lambda^{CC}$ ,  $\Phi^M$ ,  $X^M$ , and  $\tilde{R}^M$ .

$$\begin{aligned}
 P^H &= \beta^I \left[ (1 - \delta)P^H + \frac{1 - \chi^I}{\chi^I} \left( \frac{C^I}{H^I} \right)^\sigma \right] + \frac{\lambda^{CC}}{\chi^I C^{I-\sigma}} \kappa P^H, \\
 \tilde{R}^M &= \left[ 1 - \frac{\lambda^{CC}}{\chi^I C^{I-\sigma}} \right] \frac{1}{\beta^I}, \\
 M^I &= \kappa P^H H^I \quad \text{if the collateral constraint binds, and} \\
 \lambda^{CC} &= 0 \quad \text{if the collateral constraint is slack,} \\
 \Phi^M &= \Pr(\varepsilon_i \leq \bar{\varepsilon}), \\
 X^M &= \int_{X_i^M \leq 1} X_i^M f(X_i^M) dX_i^M, \\
 \tilde{R}^M &\equiv [1 - \Phi^M(1 - X^M)] R^M.
 \end{aligned}$$

## Banks

Variables to be determined:  $M^B$ ,  $N^B$ ,  $n^P$ ,  $n^B$ ,  $\lambda^{LC}$ ,  $D^B$ ,  $\Phi^D$ ,  $X^D$ , and  $\Pi^B$ .

$$\begin{aligned}M^B &= D^B + N^B, \\N^B &= n^P + (1 - \eta)n^B, \\n^P &= \eta\mathcal{E}, \\n^B &= \tilde{R}^M M^B - R^D D^B, \\ \eta\Lambda \left( \tilde{R}^M - R^D \right) &= \lambda^{LC}, \\M^B &= \psi N^B \quad \text{if the leverage constraint binds, and} \\ \lambda^{LC} &= 0 \quad \text{if the leverage constraint is slack,} \\ \Phi^D &= 0, \\ X^D &= 1, \\ \Pi^B &= \eta n^B.\end{aligned}$$

## Production

Variables to be determined:  $Y$ ,  $W$ , and  $\Pi^F$ .

$$\begin{aligned}Y &= \mathcal{K}^{1-\alpha} (L^P + L^I)^\alpha, \\W &= \alpha \frac{Y}{L^P + L^I}, \\ \Pi^F &= Y - W (L^P + L^I).\end{aligned}$$

## Market Clearing

Variables to be determined:  $C^I$ ,  $P^H$ ,  $R^D$ ,  $R^M$ ,  $S^P$ ,  $L^P$ , and  $L^I$ .

$$\begin{aligned}Y &= \mu C^P + (1 - \mu)C^I + \delta P^H \mathcal{H}, \\ \mathcal{H} &= \mu H^P + (1 - \mu)H^I, \\ D^B &= \mu D^P, \\ M^I &= (1 - \mu)M^B, \\ \mu S^P &= 0, \\ L^P &= \mu \mathcal{L}^P, \\ L^I &= (1 - \mu)\mathcal{L}^I.\end{aligned}$$

## E Appendix: Data

We use the following time series to measure the theoretical variables when assessing the performance of the model in Subsection 4.2:

1. **Output:** Real sum of *Personal Consumption Expenditures* and *Private Residential Fixed Investment* per capita (identifiers: PCE and PRFI).
2. **Consumption:** *Real Personal Consumption Expenditures* per capita (identifier: PCECC96).
3. **Real house prices:** Real *S&P/Case-Shiller U.S. National Home Price Index* (identifier: CSUSHPISA).
4. **Mortgage credit:** Real *Households and Nonprofit Organizations; Home Mortgages; Liability, Level* per capita (identifier: HHMSDODNS).
5. **Bank credit spread:** Quartered difference between the *12-Month London Interbank Offered Rate (LIBOR), based on U.S. Dollar* and the *1-Year Treasury Constant Maturity Rate* (identifiers: USD12MD156N and DGS1).
6. **Household net worth:** Real *Households and Nonprofit Organizations; Net Worth, Level* per capita (identifier: TNWBSHNO).
7. **Default rate of mortgage loans:** *Nonperforming Loans (past due 90+ days plus nonaccrual) to Total Loans for all U.S. Banks* (identifier: USNPTL).

All series are retrieved from the database of the U.S. Federal Reserve Bank of St. Louis. Series 1-2, series 4, and series 6 are transformed into per capita terms using the *Civilian Noninstitutional Population* (identifier: CNP16OV). Series 1, series 3-4, and series 6 are deflated using the *Gross Domestic Product: Implicit Price Deflator* (identifier: GDPDEF). Series 1-4 and series 6 are normalized relative to 1985Q1, then log-transformed, and lastly detrended by series-specific linear trends.

We additionally use the following time series to calibrate the model in Section 3:

1. **Share of households with loan-to-value ratios above 80 pct.:** *Table 9: Terms on Conventional Single-Family Mortgages, Annual National Averages, All Homes* in the Monthly Interest Rate Survey of the U.S. Federal Housing Finance Agency.
2. **Net dividends from commercial banks:** Sum of *Net corporate dividends: Domestic industries: Credit intermediation and related activities*, *Net corporate dividends: Domestic industries: Securities, commodity contracts, and investments*, and *Net corporate dividends: Domestic industries: Funds, trusts, and other financial vehicles* (identifiers: N3392C0A144NBEA, N3393C0A144NBEA, and N3357C0A144NBEA).
3. **Aggregate weekly hours:** *Index of Aggregate Weekly Hours: Production and Non-supervisory Employees: Total Private Industries* (identifier: AWHI).
4. **Total labor productivity:** *Early Estimate of Quarterly ULC Indicators: Total Labor Productivity for the United States* (identifier: ULQELP01USQ661S).

Series 3 is transformed into per capita terms using the *Civilian Noninstitutional Population*. Series 4 is log-transformed and then detrended by a linear trend.







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