Essays on Financial Stability and Monetary Policy

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Abstracts to Essays on Financial Stability and Monetary Policy

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This thesis consists of three self-contained chapters.

Chapter I. The first chapter develops a dynamic general equilibrium model which includes financial intermediation and endogenous financial crises. Consistent with the data, financial crises occur out of prolonged (credit) boom periods and are initiated by a moderate adverse shock. The mechanism which gives rise to boom-bust episodes around financial crises is based on an interaction between the maturity mismatch of the financial sector and an agency problem which results in procyclical lending. I show how to model these features in a tractable way, giving a realistic representation of the financial sector's balance sheet and its lending behavior. The chapter provides empirical evidence on the behavior of the U.S. financial sector's market leverage which is (i) acyclical, (ii) rose mildly prior to the Great Recession, and (iii) increased sharply during the crisis; the model is consistent with these empirical facts. It also predicts and replicates the Great Recession, when confronted with a historical series of structural shocks. Finally, the framework is extended to include price rigidities, nominal debt contracts, and monetary policy. Within this version, I analyze the impact of monetary policy on financial stability and show that a U-shaped pattern of the policy target rate is most likely to increase financial instability.

Chapter II. The second chapter models the economy as a time varying vector autoregression, consisting of economic and financial variables. The interest lies in the time varying response of these variables to a monetary policy shock. Monetary policy shocks are identified as the surprise component in policy announcements extracted from price changes in Federal Funds futures around such announcements. These monetary policy surprises enter the model as an exogenous variable. The framework is used to obtain evidence on the time varying response of stock prices to the monetary policy surprises. Stock prices always persistently decrease following a monetary tightening and more strongly than fundamentals imply - with an increase in risk-premia accounting for the difference. However, the response of stock prices varies over time. They decrease less during a boom and a perceived bubble period than during a recession. The findings suggest that so-called "leaning against the wind policies" may be ineffective since stock prices are less responsive during periods when such policies would disinflate asset bubbles using contractionary monetary policy.

Chapter III. The third chapter augments a monetary dynamic general equilibrium model with a bubble as considered in Miao and Wang (2015). A bubble may exist in firms' stock market values and firms borrow against their inflated stock market values. Within this framework, I analyze the relation between monetary policy and the bubble. I find that contractionary monetary policy decreases the bubble which tightens borrowing constraints and amplifies the reaction of investment and output. These results are in contrast to the ones in Galí (2014) who considers a bubble of the classic rational type and finds that contractionary monetary policy can increase bubbles.

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To my parents, Mami und Papi.

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Contents

Chapter I

Financial Crises & Debt Rigidities

1 Introduction

This chapter embeds occasional financial crises into a macroeconomic model, such that the behavior of the economy around financial crises is consistent with three empirical observations. First, financial crises occur out of (credit) boom periods as shown by Schularick and Taylor (2012) and Boissay, Collard and Smets (2015) among others. This empirical fact poses a challenge to models, in which agents build up precautionary buffers in good times and the likelihood of a financial crisis may therefore decrease. Second, financial crises can be the response to relatively small initial triggers. For example, the initial trigger for the Great Recession originated from the subprime mortgage credit market and the losses with respect to this market were relatively small (Gorton and Ordonez, 2014). The third empirical observation concerns the risk-taking of the financial sector as indicated by the behavior of its leverage around financial crises and over the business cycle. Often expressed views in the literature are that financial institutions (i) strongly increased their leverage prior to the Great Recession, (ii) had to deleverage during the crisis, and (iii) leverage is procyclical.[1] However, such conclusions are often based on using book value data which does not necessarily reflect current market prices, since book values are infrequently updated. In this chapter, I obtain an empirical measure of *market leverage* for the U.S. financial sector which is derived from bank-level datasets and behaves quite differently (see Appendix A.9 for a description of the data and derivations). The path of market leverage around the Great Recession is shown in Figure (1).[2] Even though financial institutions strongly expanded their balance sheets prior to the Great Recession - increasing their debt and assets - market leverage remained relatively stable and rose only mildly. Why? Because asset prices were also elevated - lowering leverage. In contrast, prices collapsed during the crisis, faster than intermediaries were able to reduce their debt burden which they accumulated before the crisis, leading to a sharp spike of leverage; and, as shown below, the derived measure of market leverage is *acyclical.* In order to ensure a consistent comparison between data and model, I differentiate between the financial sector's

[1] Adrian and Shin (2010) show that leverage of certain financial institutions is procyclical based on book value data.

[2] Similar empirical evidence can be found in Ang, Gorovyy and van Inwegen (2011).

book and market leverage in the model and show that the behavior of both measures around financial crises and their cyclicality are in line with their empirical counterparts; indicating that the model approximates well the risk-taking of the financial sector as reflected in the data.

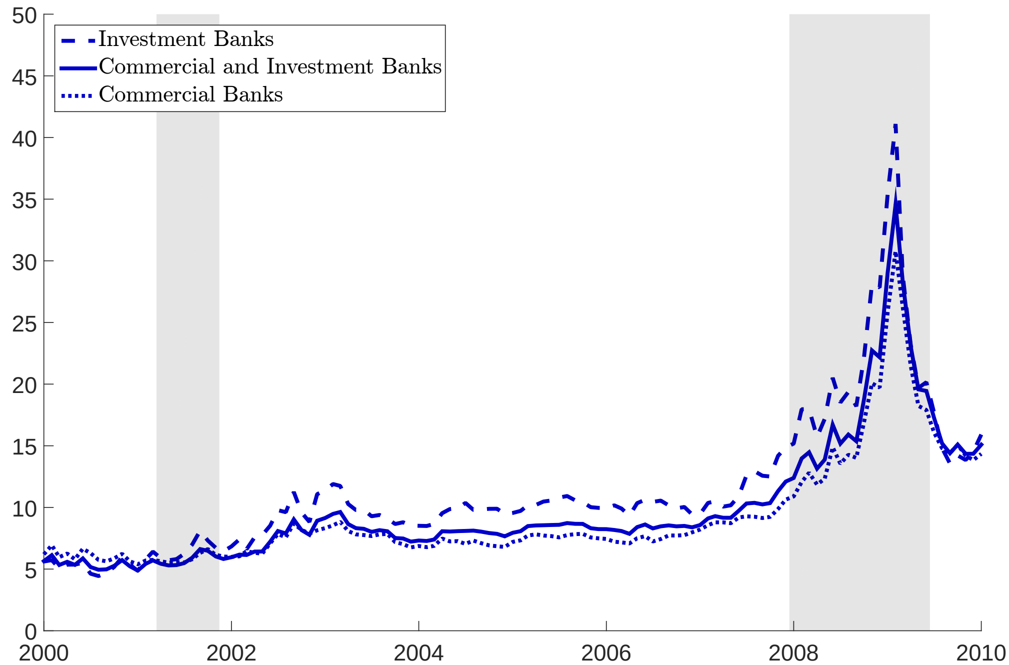

Figure 1: ***Market Leverage.*** *The graph shows the evolution of a proxy for market leverage around the Great Recession (market value of assets / market value of equity), differentiating between types of U.S. financial institutions. See Appendix A.9 for a description of the data and derivations. Grey bars denote NBER recessions.*

Maturity Mismatch and Procyclical Lending. The crucial elements of the model are the maturity mismatch of the financial sector and an agency problem which results in procyclical lending. The former is an institutional characteristic of the financial sector, given its role in transforming short-term borrowing into long-term lending. In the model, intermediaries borrow short-term debt from households and issue long-term and defaultable debt to entrepreneurs. Since lending is long-term, only a fraction of it matures each period. Non-matured loans exist for multiple periods and cannot be restructured - *debt is rigid*. The model therefore distinguishes between *outstanding loans* and *newly issued loans*. Empirical evidence suggests that new lending is procyclical - both volume as well as lending standards which tighten during recessions and ease in boom periods. Figure (2) shows the percentage change from a year ago of U.S. commercial banks' lending, which strongly declines during recessions and picks up afterwards. Figure (3) shows the net percentage of senior loan officers reporting a tightening of lending standards in a survey conducted by the U.S. Federal Reserve. Again, lending standards tighten during recessions and ease subsequently. In order to reconcile the model with these empirical facts, I introduce an agency problem between intermediaries and entrepreneurs which determines lending volume and standards over the business cycle. Entrepreneurs may want to risk-shift and invest in projects with low expected

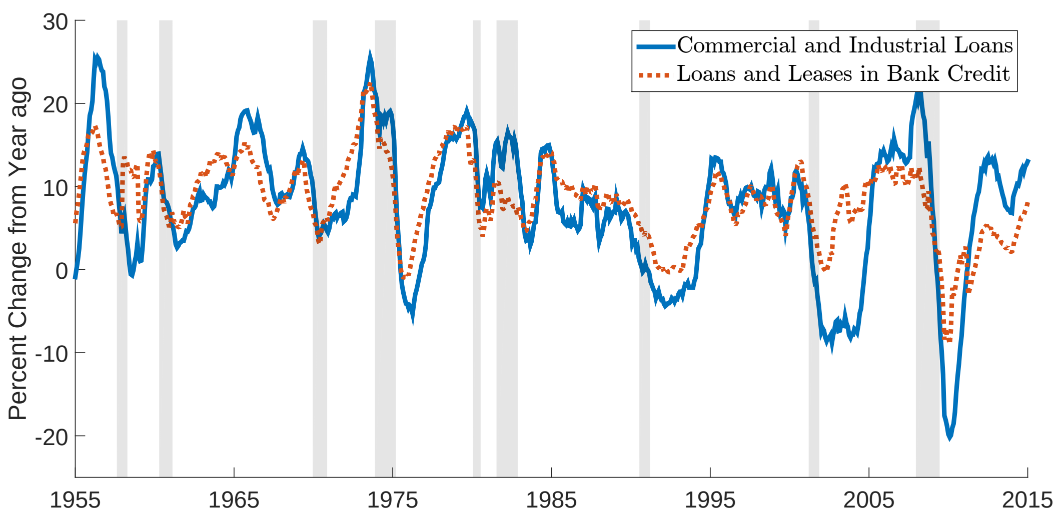

Figure 2: ***Procyclical Lending.*** *Percentage change from year ago of U.S. commercial banks' commercial and industrial loans (blue, solid) and total loans and leases in bank credit (red, dotted). Source: Federal Reserve Bank of St. Louis. Grey bars denote NBER recessions.*

returns, but potentially high upsides which imply a negative net present value investment for financial intermediaries. Credit is rationed to ensure that entrepreneurs do not invest into such projects (similar to Stiglitz and Weiss, 1981). This risk-shifting problem becomes more severe in recessions as the incentives to risk-shift increase. The quantity and standards (loan-to-collateral ratio) of newly issued loans therefore decrease in recessions; while the opposite holds for booms. In addition, the default decision of entrepreneurs is endogenous and the model therefore incorporates an *endogenous credit risk cycle*.

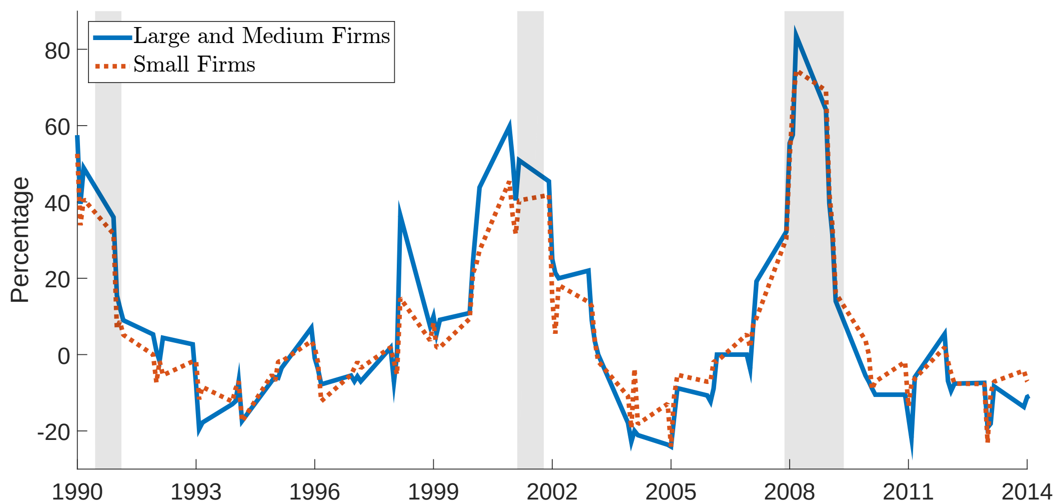

Figure 3: ***Procyclical Lending.*** *Senior Loan Officer Opinion Survey on Bank Lending Practices. Net percentage of domestic banks reporting a tightening of standards for commercial and industrial loans to large and medium firms (blue, solid) and small firms (red, dotted). Source: Federal Reserve Bank of St. Louis. Grey bars denote NBER recessions.*

Boom-Bust-Cycle. The maturity mismatch of the financial sector and its procyclical lending give rise to boom-bust episodes around financial crises - characterized by the following sequence of events. During a prolonged boom period, intermediaries expand their balance sheets. They take on more debt and replace old, maturing loans with new loans which are backed by relatively less collateral because incentives to risk-shift decrease in good times and firms are less likely to default. The increase of the financial sector's liabilities is partly fuelled by the household's desire to smooth consumption and save during the boom, resulting in a decline of the real interest rate on short-term debt. The longer the boom lasts, the stronger the financial sector's balance sheet expansion and the larger the fraction of loans which has been issued under good economic conditions. The behavior of the financial sector's market leverage is determined by two opposing effects. On the one hand, outstanding loans constantly increase in value - lowering leverage. On the other hand, the financial sector takes on more debt in order to issue more new loans - increasing leverage. The latter effect dominates, such that market leverage mildly increases during a prolonged boom period as in Figure (1). However, following an adverse shock, leverage can also increase in the short run as during the Great Recession shown in Figure (1). After an adverse shock, current and future default ratios increase - most strongly for loans backed by less collateral - dragging down loan values and increasing market leverage. Due to the maturity mismatch, the financial sector is left with a portfolio of outstanding, non-performing loans and is unable to quickly reduce its increased debt burden from the boom or raise new equity to lower its leverage.

Endogenous Financial Crises. When the financial sector's market leverage exceeds a certain threshold, creditors doubt that they will be repaid and run on intermediaries. A creditor run results in a discontinuous drop in the amount of funding available to the financial sector. Since creditor runs only occur if the intermediary's leverage exceeds a certain threshold, they are linked to the balance sheet of the financial intermediary. In particular, they are not self-confirming equilibria in a setting with multiple equilibria as in Diamond and Dybvig (1983). Gorton (1988) gives empirical evidence for this approach. He shows that banking panics during the U.S. National Banking Era were systematic responses by depositors to changing perceptions of risk, based on the arrival of new information rather than random events. In the model, a restriction of available funding to the financial sector is transmitted to the rest of the economy through a contraction of new lending - a credit crunch.

Taken together, the model includes standard business cycle dynamics, a realistic representation of the financial sector's balance sheet and its lending behavior, and endogenous financial crises. Capturing these dynamics in one model is particularly important since I am interested in studying the preconditions under which financial crises are most likely to occur. Given a calibrated version of the model which matches the frequency and severity of crises in the data, I find that the typical build-up path leading to a financial crisis is characterized by a prolonged boom period, followed by a sudden bust which is triggered by a relatively moderate adverse shock. The boom increases the likelihood of a financial crisis due to the rise of the financial sector's leverage in good times - allowing it to take advantage of the good investment opportunities while building up financial fragility. Moreover, the model is able to replicate three stylized facts regarding banking crises as highlighted by Boissay, Collard and Smets (2015): financial crises are rare, break out in the midst of a credit-intensive boom, and the associated recessions are deeper than standard recessions. The behavior of the economy around 'standard' recessions is different, since they are not preceded by an expansion of the financial sector's balance sheet or a credit boom. I check the model's performance in two additional ways. First, it is confronted with a historical series of structural shocks and the results show that the model is able to predict and replicate the occurrence of the Great Recession - while the probability of a crisis in the near future is close to zero for the rest of the sample. Second, as targeted, I show that the financial sector's *book and market leverage* behave as their empirical counterparts around financial crises and over the business cycle.

The rest of the chapter is organized as follows. The next section relates the model to the literature. Section 3 illustrates the main mechanism with the help of a partial equilibrium example. Section 4 considers a real model which is quantitatively analyzed. Section 5 concludes. Appendix B extends the real model to a nominal version by including price rigidities, nominal debt contracts, and monetary policy. In this framework, I analyze the impact of monetary policy on financial stability and show that a U-shaped pattern of the policy target rate is most likely to increase financial instability - a pattern observed in the U.S. and in Japan prior to the recent financial crises in those countries.

2 Related Literature

This chapter builds on past contributions to the literature on financial frictions within macroeconomic settings. The seminal contributions in this field by Bernanke and Gertler (1989), Kiyotaki and Moore (1997), and Carlstrom and Fuerst (1997) focus on the role of financial frictions in the amplification and persistence of shocks during business cycle episodes. This chapter considers a (monetary) dynamic general equilibrium model similar to Bernanke, Gertler and Gilchrist (1999). The model differs in comparison to the mentioned contributions along three dimensions. First, financial intermediaries are modeled explicitly. Second, occasional financial crises are introduced. Third, the model is solved nonlinearly. In this regard, the chapter contributes to a recent literature which developed after the Great Recession. In what follows, I explain how the model relates to existing contributions within this literature.

Mendoza (2010), Bianchi (2011), and Bianchi and Mendoza (2010) study financial crises and sudden stops within small open economy (or partial equilibrium) settings. In their models, (firm-)households are subject to a leverage constraint which binds occasionally. As here, leverage determines the distance to a financial crisis. In contrast to these contributions, I consider a closed economy in a general equilibrium setting and model financial intermediaries explicitly. Brunnermeier and Sannikov (2014), Adrian and Boyarchenko (2012), and He and Krishnamurthy (2014) build models which incorporate financial intermediation. These models are parsimonious on the modeling of the macroeconomy, have few state variables, and are written in continuous time. Brunnermeier and Sannikov (2014) show that endogenous systemic risk remains even if exogenous risk decreases because agents adjust their risk-taking behavior; endogenous systemic risk can even increase if exogenous risk decreases, a result which is termed "volatility paradox".

Motivated by the research of Adrian and Shin (2010), Adrian and Boyarchenko (2012) construct a model in which financial intermediaries' leverage is procyclical since intermediaries raise their debt according to a value-at-risk constraint. Here, in contrast to Adrian and Boyarchenko (2012), financial intermediaries are unconstrained in their funding in normal times and occasionally experience a discontinuous drop in the amount of funding available to them if a creditor run occurs. In He and Krishnamurthy (2014), the amount of equity relative to the market value of assets which financial intermediaries can raise is determined by their contemporaneous return on equity. In a crisis, intermediaries experience low returns on equity, restricting the available amount of equity, and increasing their market leverage. The behavior of leverage around a financial crisis in He and Krishnamurthy (2014) is therefore similar to the one in this model. However, the mechanism is different. Here, intermediaries are unable to raise equity. In a crisis, their market leverage increases because the value of assets falls faster than intermediaries are able to reduce their debt burden.

Further contributions to the aforementioned literature are Boissay, Collard and Smets (2015), Bocola (2015), Martinez-Miera and Suarez (2012), and Gertler and Kiyotaki (2015). The closest paper to this one is Boissay, Collard and Smets (2015). In their paper, financial crises occur out of credit booms and are initiated by relatively moderate adverse shocks - as in this one. What differentiates the chapter from Boissay, Collard and Smets (2015) is the mechanism. The one in their paper works as follows. After a boom period, when productivity returns, households continue to accumulate savings which increases the available funds in financial markets. The increased availability of funding gives banks incentives to engage in risky activities which can result in a collapse of the interbank market. In contrast to Boissay, Collard and Smets (2015), in this chapter it is the interaction between the maturity mismatch of intermediaries and their procyclical lending, with the described behavior of leverage, which play the key roles for the boom-bust-cycle. Similar ideas can be found in the work of John Geanakoplos (see for example Fostel and Geanakoplos, 2008).

Bocola (2015) focuses on sovereign risk and solves a model with a similar number of state variables, using a comparable solution algorithm to handle the curse of dimensionality. Additionally, he shows how to estimate the model using Bayesian techniques. Martinez-Miera and Suarez (2012) study welfare effects of capital requirements within a model in which banks risk-shift due to government guarantees and endogenously expose themselves to exogenous systemic risk. And, similar to Gertler and Kiyotaki (2015), this chapter shows how to embed occasional creditor/bank runs into an infinite horizon economy.

This chapter contributes to this literature along three dimensions. First, it illustrates that the interaction between the financial sector's maturity mismatch and its procyclical lending can drive boom-bust cycles around financial crises; long-term defautable debt is modeled in a tractable way which gives a realistic representation of the financial sector's balance sheet.[3] Second, the chapter provides empirical evidence on the U.S. financial sector's market leverage around financial crises and over the business cycle, as mentioned in the introduction; the model is consistent with these empirical facts. Third, all of the mentioned contributions are real models. In contrast, this chapter extends the real model in the main analysis to a nominal model in which the non-neutrality of monetary policy arises due to price stickiness and nominal debt contracts under default and default costs (similar to Gomes, Jermann and Schmid, 2014). To the best of my knowledge, this is the first paper which introduces financial crises into a standard New-Keynesian dynamic general equilibrium model and obtains a global solution of the model.[4]

[3]Andreasen, Ferman and Zabczyk (2013) illustrate how to introduce maturity transformation within a general equilibrium model. I follow their reasoning by assuming that long-term loans exist because firms face long-term projects. In contrast to Andreasen, Ferman and Zabczyk (2013), firms can additionally default on their long-term loan.

[4]Brunnermeier and Sannikov (2012) also study the impact of monetary policy on financial stability. In contrast to this chapter, their framework puts financial frictions at the center of the monetary policy transmission mechanism. The main role of monetary policy in their model is to redistribute wealth towards financially constrained agents in order to avoid deflationary spirals after adverse shocks. In contrast to their paper, monetary policy is non-neutral in this model due to price rigidities.

3 A Partial Equilibrium Example

I start out by giving a stylized partial equilibrium example of the main mechanism. The purpose of this section is to convey the central ideas of the general equilibrium models which follow. Consider a representative financial intermediary holding zero-interest, short-term debt B_t and long-term, defaultable loans with face value L_t in period t. The loans L_t are backed by collateral K_t which is valued at Q^K_{t+k} in period $t+k$. Assume that loans have an exogenous stochastic maturity. They do not mature with probability γ and are only repaid if they mature. The price per unit of loan is given by

$$Q_t = \mathbb{E}_t\left[\sum_{k=1}^{\infty}\gamma^{k-1}(1-\gamma)\Pi_{t+k}\left(\frac{L_t}{K_t}, \omega Q^K_{t+k}\left[\{\epsilon_t\}_{t=0}^{t+k}\right]\right)\right]$$

where Π_{t+k} is the repayment per unit of face value in period $t+k$ and ω is some idiosyncratic shock, determining the value of collateral to individual borrowers. The repayment may be smaller than one because borrowers have the option to default in which case less than the face value is recovered. Assume that all borrowers start out with the same $\frac{L_t}{K_t}$-ratio and decide to default in period $t+k$ if $L_t > \omega Q^K_{t+k}K_t$ - the face value of the loan is larger than the value of collateral. Π_{t+k} depends on Q^K_{t+k} which in turn is positively related to the history of some exogenous aggregate source of risk ϵ_t from period 0 until $t+k$, and therefore $\frac{\partial \Pi_{t+k}}{\partial \epsilon_x} > 0$ for $x \in \{0, 1, .., t+k\}$. Moreover, default is more likely the higher the loan-to-collateral ratio, hence $\frac{\partial \Pi_{t+k}}{\partial \frac{L_t}{K_t}} < 0$. Given the pricing of loans, the market leverage of the financial intermediary can then be defined as $Lev_t \equiv \frac{B_t}{Q_t L_t}$.

Assume further that the economy has experienced a prolonged boom until period t characterized by several positive realisations of the exogenous source of risk. During the boom period, intermediaries expanded their balance sheets by increasing their debt B_t to issue more loans backed by relatively less collateral, such that L_t and $\frac{L_t}{K_t}$ increased. However, even though the size of the intermediary's balance sheet grew during the boom, assume that its market leverage increased only mildly since Q_t remained high as collateral values Q^K_{t+k} are expected to stay high and default ratios low. The economy enters period $t+1$. During this period, the intermediary does not issue any new loans, does not pay out dividends, and cannot raise equity. The financing gap of the financial intermediary in period $t+1$ can be written as

$$\text{Gap}_{\text{t+1}} = \underbrace{(\gamma Q_{t+1} L_t + B_t)}_{\text{Expenses}} - \underbrace{(\gamma Q_{t+1} L_t + (1-\gamma) L_t \Pi_{t+1})}_{\text{Income}}$$

stating that the intermediary receives income from the repayment of maturing loans and the selling of non-maturing loans, while it has to repay its outstanding debt B_t and purchases non-matured loans. The financing gap simplifies to

$$\text{Gap}_{\text{t+1}} = B_t - (1-\gamma) L_t \Pi_{t+1}$$

since the financial intermediary is the sole buyer of financial assets. Assume that the economy experiences a sudden bust in period $t+1$ such that ϵ_{t+1}, Q^K_{t+k} and Π_{t+k} for $k \geq 1$ are low. Next, consider two cases. First, the case in which loans are short-term, $\gamma = 0$, and there is no maturity mismatch. Then, the intermediary is solvent if $L_t \Pi_{t+1} > B_t$ and the financing gap is negative or put differently, the net worth is positive. In this case, there is no rigidity with respect to the intermediary's balance sheet. Given a positive net worth, the intermediary is completely free to choose its new debt - and if one considers new investments, then also its new loans, the loan-to-collateral ratio on new loans, and hence its leverage. In contrast, consider next the case in which loans are long-term, $0 < \gamma < 1$, and the intermediary runs a maturity mismatch. In this case, the financing gap is $B_t - (1-\gamma) L_t \Pi_{t+1}$ which is likely to be positive, in particular if profits are low. The amount of new debt B_{t+1} has to cover at least this gap. The intermediary's leverage is then given by $Lev_{t+1} = \frac{B_{t+1}}{Q_{t+1} \gamma L_t}$ and the price of the non-matured loans γL_t is

$$Q_{t+1} = \mathbb{E}_t \left[\sum_{k=2}^{\infty} \gamma^{k-2} (1-\gamma) \Pi_{t+k} \left(\frac{L_t}{K_t}, \omega Q^K_{t+k} \left[\{\epsilon_t\}_{t=0}^{t+k} \right] \right) \right]$$

which is low due to the fall in Π_{t+k} for $k \geq 1$. The leverage is higher the lower the price of non-matured loans, $\frac{\partial Lev_{t+1}}{\partial Q_{t+1}} < 0$, and the larger the initial stock of debt, $\frac{\partial Lev_{t+1}}{\partial B_t} > 0$, which has to be serviced. Hence, if the adverse shock is large enough, the intermediary's leverage is going to increase, especially if restrictions on raising equity exist and loans cannot be sold to an outsider. In the case of a maturity mismatch, the intermediary is unable to work against these effects in the short run since it is not entirely free to choose the structure of its balance sheet, but instead the amount of new debt B_{t+1}, overall loans in period $t+1$, and the associated loan-to-collateral ratios are partly set by the legacy assets, collateral, and liabilities. In this sense, the maturity mismatch plays an important role in the bust since it increases the rigidity of the financial sector's balance sheet.

Assume next that creditors run on the financial intermediary in period $t+1$ if its leverage Lev_{t+1} exceeds a certain threshold. The likelihood of such a run increased during the preceding boom, since the intermediary mildly increased its leverage, approaching the threshold. Hence, a smaller adverse shock is needed, such that its leverage is going to exceed the threshold. Moreover, loans which were issued during the boom have a higher loan-to-collateral ratio and their default ratios therefore increase most strongly after an adverse shock which lowers collateral values. In turn, this affects the intermediary's leverage by lowering loan values Q_{t+1}, again increasing leverage Lev_{t+1}.

This simple example can be used to interpret Figure (1). During the run-up to the Great Recession, intermediaries expanded their balance sheets by issuing more loans and acquired more debt, but their market leverage increased only slowly since prices were elevated. However, after the sudden bust, intermediaries' leverage spiked sharply since they held a portfolio of non-performing loans and the prices of these loans fell faster than they were able to decrease their debt burden, causing further problems between intermediaries and creditors. Next, these ideas are incorporated into an infinite-horizon, discrete-time production economy.

4 Real Model

4.1 Household

Following Greenwood, Hercowitz and Huffman (1988), the representative household values consumption C_t and dislikes labor H_t captured by the flow utility

$$U\left(C_t, H_t\right) = log\left(C_t - \chi \frac{H_t^{1+\phi}}{1+\phi}\right)$$

where ϕ represents the inverse Frisch elasticity of labor supply. The household chooses contingent plans for consumption, labor supply, and savings, in the form of short-term and riskless bonds B_t^H, so as to maximize lifetime utility, while discounting the future at the rate β^H. Taking prices, wages, and interest rates as given, the household solves the problem

$$V^H\left(B_{t-1}^H, \mathbb{S}_t\right) \quad = \quad \underset{C_t, H_t, B_t^H}{max} \left\{U(C_t, H_t) + \beta^H \mathbb{E}\left[V^H\left(B_t^H, \mathbb{S}_{t+1}\right)\right]\right\}$$

subject to

$$\begin{aligned} C_t + \frac{B_t^H}{R_{t+1}} &\leq w_t H_t + B_{t-1}^H + T_t \\ \mathbb{S}_{t+1} &= \Gamma(\mathbb{S}_t) \end{aligned}$$

where w_t is the real wage and R_{t+1} is the real interest rate on short-term bonds between period t and $t+1$ which is known in period t. $\Gamma(.)$ denotes the law of motion for aggregate state variables $\mathbb{S}_t$ and the expectation $\mathbb{E}\left[.\right]$ is formed conditional on the information set $\mathbb{S}_t$ at time t. Moreover, the household receives lump-sum transfers T_t from firms, described in more detail below. The solution to the above problem gives the inter- and intratemporal optimality conditions

$$\begin{aligned} 1 &= \mathbb{E}\left[\Lambda_{t,t+1}\right] R_{t+1} \\ w_t &= \chi H_t^{\phi} \end{aligned}$$

where

$$\Lambda_{t,t+1} = \beta^H \left(\frac{C_t - \chi \frac{H_t^{1+\phi}}{1+\phi}}{C_{t+1} - \chi \frac{H_{t+1}^{1+\phi}}{1+\phi}} \right)$$

is the household's stochastic discount factor.

4.2 Good Production

A representative good producer operates according to a Cobb-Douglas production function

$$Y_t = A_t K_{t-1}^{\alpha} H_t^{1-\alpha} \tag{1}$$

combining labor H_t supplied by the household with aggregate capital K_{t-1} supplied by entrepreneurs in period $t-1$ in order to produce the good Y_t. The only source of aggregate risk in the model enters via the technology level A_t

$$\begin{aligned} A_t &= e^{a_t} \\ a_t &= \rho_a a_{t-1} + \epsilon_t^a \\ \epsilon_t^a &\sim N(0, \sigma_a^2) \end{aligned}$$

where ϵ_t^a is termed the technology shock. Factor markets are competitive, and, as a result, all available factors are employed and pay their marginal products, which are given by

$$\begin{aligned} w_t &= (1-\alpha)\frac{Y_t}{H_t} \\ r_t^K &= \alpha \frac{Y_t}{K_{t-1}} \end{aligned}$$

where r_t^K is the rental rate per unit of capital. The role of financial intermediation is to transform the household's short-term savings B_t^H into investment in the economy's aggregate capital stock K_t which enters the production function of the good producer in period $t+1$. The two types of agents which fulfill this role, the financial intermediary and entrepreneurs, are at the heart of the model. The intermediation chain is summarized in Figure (4).

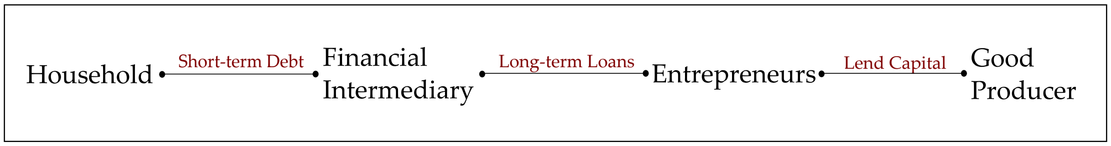

Figure 4: *Intermediation chain.*

4.3 Entrepreneurs

First, the evolution of long-term debt and the entrepreneurs' default decision are introduced for a given newly issued loan. The next section outlines the agency problem between entrepreneurs and the financial intermediary which determines the amount of newly issued loans.

4.3.1 Stochastic Maturity and Default

An entrepreneur who acquires a loan in period t is termed a 'new' entrepreneur in that period (highlighted by the superscript new). There is a unit mass of new entrepreneurs and since all new entrepreneurs turn out to be identical, I omit entrepreneur-specific notation. A new entrepreneur has net worth N_t and acquires a long-term, collateralized, and defaultable loan $Q_t L_t^{new}$ from the financial intermediary (both net worth and loan value are determined shortly). Combining N_t and $Q_t L_t^{new}$, the entrepreneur purchases K_t^{new} units of capital

$$Q_t^K K_t^{new} = N_t + Q_t L_t^{new}$$

where Q_t^K denotes the price of capital and Q_t the price of long-term loans. The underlying collateral of the loan are the units of capital K_t^{new} which an entrepreneur purchases and the face value of the loan is L_t^{new} which the entrepreneur has to repay to the intermediary. The capital is lent to the good producer and the returns on the entrepreneurs' investments are risky, since the amount of capital is chosen at least one period in advance.

In order to keep the model tractable and the number of aggregate state variables to a minimum, long-term debt is introduced as follows. Each loan has an exogenous stochastic maturity and matures with probability $1 - \gamma$ in the next period. An entrepreneur with a non-maturing loan dating from period t does not have to make a payment to the financial intermediary, but receives the rental rate r^K_{t+k} per unit of capital in period $t+k$ for $k \in \{1, 2, ..., \infty\}$ from the good producer. These profits are transferred lump-sum to the household. The underlying collateral K^{new}_t of a non-maturing loan stays constant as the household refurbishes depreciated capital δK^{new}_t where δ is the rate of depreciation.[5] Moreover, the face value L^{new}_t remains unchanged as an entrepreneur does not have to make a payment to the financial intermediary if the loan does not mature.[6]

If a still outstanding loan, initially given out in period t, matures in period $t+k$, then the entrepreneur receives the rental rate r^K_{t+k} per unit of capital and sells the remaining capital for the price Q^K_{t+k}. Additionally, the profits of a maturing loan are hit by an idiosyncratic shock ω, with $\omega \sim U[1-b, 1+b]$ which is normalized to have mean unity and is drawn independently across time and entrepreneurs.[7] The overall profits are

$$\omega R^K_{t+k} Q^K_{t+k-1} K^{new}_t$$

where $R^K_{t+k} \equiv \frac{(Q^K_{t+k}(1-\delta)+r^K_{t+k})}{Q^K_{t+k-1}}$. An entrepreneur compares these profits to the face value of debt L^{new}_t and decides whether to default on its obligation to repay or not. An entrepreneur defaults if L^{new}_t is larger than the entrepreneur's profits $\omega R^K_{t+k} Q^K_{t+k-1} K^{new}_t$. Or put differently, if the idiosyncratic shock ω is lower than a threshold level $\overline{\omega}_{t+k|t}$ in period $t+k$ which depends on the aggregate profits to capital $R^K_{t+k} Q^K_{t+k-1}$ and the loan-to-collateral ratio $\frac{L^{new}_t}{K^{new}_t}$ for a loan issued in period t.

[5]This assumption ensures that the probability of default of very old entrepreneurs does not approach one since their underlying capital and therefore their profits do not approach zero.

[6]This assumption implies no default considerations before a loan matures which makes the problem tractable and aggregation feasible as shown in Appendix A.1.

[7]One could also add an idiosyncratic shock on the profits of a non-maturing loan. However, this would not change the model since these profits are transferred lump-sum to the household and would therefore wash out in the aggregate if such an idiosyncratic shock has mean unity. For simplicity, it is therefore omitted in the above description.

Default Decision. *An entrepreneur from period t whose loan matures in $t+k$ where $k \in \{1, 2, ..., \infty\}$ defaults iff*

$$\omega < \overline{\omega}_{t+k|t}$$

where

$$\overline{\omega}_{t+k|t} \equiv \frac{L_t^{new}}{R_{t+k}^K Q_{t+k-1}^K K_t^{new}} \tag{2}$$

Equation (2) highlights that the model incorporates vintage-specific default thresholds $\overline{\omega}_{t+k|t}$ which depend on the face value of debt L_t^{new} and the underlying collateral K_t^{new} from period t. Loans issued in different periods under distinct states of the economy can therefore have different default thresholds when maturing in the same period $t+k$. The following simple example illustrates this point.

Example. *If the loan-to-capital ratios of loans issued in periods $t-2$ and $t-1$ are such that*

$$\frac{L_{t-2}^{new}}{K_{t-2}^{new}} > \frac{L_{t-1}^{new}}{K_{t-1}^{new}} \quad ,$$

and these loans are maturing in period t, then their default thresholds in period t relate according to

$$\overline{\omega}_{t|t-2} = \frac{L_{t-2}^{new}}{R_t^K Q_{t-1}^K K_{t-2}^{new}} > \frac{L_{t-1}^{new}}{R_t^K Q_{t-1}^K K_{t-1}^{new}} = \overline{\omega}_{t|t-1}$$

The loan with a higher loan-to-capital ratio also has a higher default threshold, because both receive the same aggregate profits $R_t^K Q_{t-1}^K$ per unit of capital.

If an entrepreneur defaults, then $(1-\mu)\omega R_{t+k}^K Q_{t+k-1}^K K_t^{new}$ is recovered by the financial intermediary where μ is the fraction of profits lost and reflects the costs of default. If an entrepreneur does not default, L_t^{new} is repaid to the financial intermediary and the remaining profits $\omega R_{t+k}^K Q_{t+k-1}^K K_t^{new} - L_t^{new}$ are equally split among new entrepreneurs in period $t+k$ which ensures that all new entrepreneurs start with the same amount of net worth. New entrepreneurs consist of all entrepreneurs whose loans matured (whether they defaulted or not), ensuring that the number of entrepreneurs stays constant. An interpretation of the above specification is that firms face long-term projects during which their capital remains fixed and they take on long-term debt in order to finance these projects. The model is therefore in line with the observation that firms infrequently change their capital stock and borrowing. Figure (5) summarizes the described set-up of long-term debt under stochastic maturity and default.

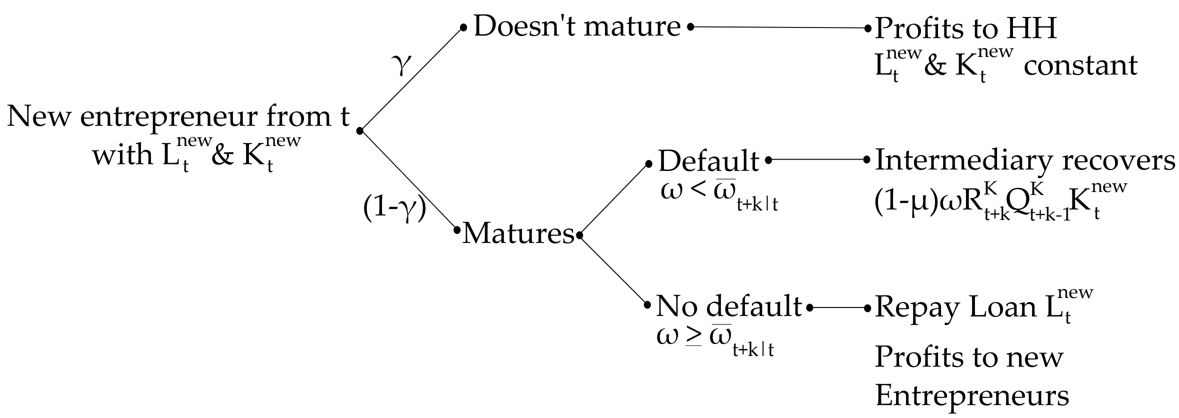

Figure 5: *Long-term debt under stochastic maturity and default.*

4.3.2 Risk-shifting problem

A new entrepreneur cannot only invest in the described project, which I term the "good project", but also into a second project which is called the "bad project". A project is chosen when a loan is taken up and an entrepreneur cannot switch projects for the duration of the loan contract. The properties of the bad project are as follows.

Bad Project. *The good and bad project only differ in the properties of the distribution from which the idiosyncratic shock is drawn which hits an entrepreneur's profits when his loan matures. The profits under the bad project are denoted* $\widetilde{\omega} R^K_{t+k} Q^K_{t+k-1} K^{new}_t$ *with* $\widetilde{\omega} \sim U[\widetilde{k}-\widetilde{c}, \widetilde{k}+\widetilde{c}]$ *which is independent across entrepreneurs and time. It is assumed that* $\widetilde{c} > b$ *and* $\widetilde{k} < 1$*, i.e.* $\widetilde{\omega}$ *has a higher variance and a lower mean compared to* ω*.*

In the model's equilibrium under reasonable parameter values, such that the bad project is sufficiently different from the good project, it can be shown that the above assumptions ensure that lending to entrepreneurs, who invest in the bad project, is a negative net present value investment for the financial intermediary. In contrast, a leveraged entrepreneur may prefer the bad project over the good project, due to the possibility to take up a loan under limited liability and due to the higher variance (and therefore the higher potential upside) of the bad project. Under the assumption that the debt contract cannot be conditioned on the type of the project, the financial intermediary would therefore never agree to contracts for which entrepreneurs have the incentive to invest into the bad project. Hence, any agreement must satisfy the incentive compatibility (IC) constraint which demands that the entrepreneur's objective function under the good project V_t^{good} is at least as large as the objective function under the bad project V_t^{bad}, i.e.

$$V_t^{good} \geq V_t^{bad} \tag{3}$$

Knowing that any debt contract with the financial intermediary has to satisfy the IC constraint at the time when a contract is negotiated, inequality (3) directly enters as a constraint into a new entrepreneur's decision problem. Given the net worth from maturing entrepreneurs N_t and the price of new debt Q_t, a risk-neutral, new entrepreneur chooses the amount of debt L_t^{new} to take on and the units of capital K_t^{new} to purchase.[8] The complete decision problem can be written as

[8] The net worth of a new entrepreneur is given by $N_t = (1-\gamma)\sum_{j=1}^{\infty}\int_{\overline{\omega}_{t|t-j}}^{1+b}\left(\omega R_t^K Q_{t-1}^K K_{t-j}^{new} - L_{t-j}^{new}\right) d\Phi(\omega)$.

$$\max_{K_t^{new},L_t^{new}} V_t^{good} = \mathbb{E}\left[\sum_{k=1}^{\infty}\gamma^{k-1}\Lambda_{t,t+k}\left\{(1-\gamma)\int_{\overline{\omega}_{t+k|t}}^{1+b}(\omega R_{t+k}^K Q_{t+k-1}^K K_t^{new} - L_t^{new})d\Phi(\omega) + \gamma r_{t+k}^K K_t^{new}\right\}\right] \quad (4)$$

subject to

$$\begin{aligned} Q_t^K K_t^{new} &= N_t + Q_t L_t^{new} && (5) \\ \overline{\omega}_{t+k|t} &= \frac{L_t^{new}}{R_{t+k}^K Q_{t+k-1}^K K_t^{new}} \quad for \;\; k \in \{1, 2, ..., \infty\} && (6) \\ V_t^{good} &\geq V_t^{bad} && (7) \\ \mathbb{S}_{t+1} &= \Gamma(\mathbb{S}_t) \end{aligned}$$

where $\Phi(\omega)$ is the c.d.f. for ω and V_t^{bad} is defined equivalent to V_t^{good}, taking into account the properties of the idiosyncratic shock $\widetilde{\omega}$ under the bad project stated above. The entrepreneur's objective function V_t^{good} captures both the profits if the loan matures and the entrepreneur does not default (the first term in the curly bracket) as well as the profits received until the loan matures (the second term in the curly bracket). Constraint (5) is the entrepreneur's budget constraint. The constraints summarized in (6) define the future default thresholds $\overline{\omega}_{t+k|t}$ and constraint (7) gives the IC constraint. For the chosen calibration which ensures that the bad project is sufficiently different to the good project, it can be shown that the IC constraint is always binding, since the derivative of V_t^{good} with respect to L_t^{new} is positive at the point where V_t^{good} and V_t^{bad} intersect. Figure (6) illustrates this point, plotting V_t^{bad} and V_t^{good} against the amount of real new debt $Q_t L_t^{new}$, based on the calibration in section *4.7*. V_t^{bad} intersects V_t^{good} exactly once from below. The intersection determines the amount of debt $Q_t L_t^{new}$ a new entrepreneur can raise - given net worth, prices, and interest rates. At the intersection, the entrepreneur would therefore prefer to borrow more, but cannot, because a higher amount of debt would induce the entrepreneur to switch to the bad project. Since the IC constraint is binding, the entrepreneur's decision problem is largely simplified.

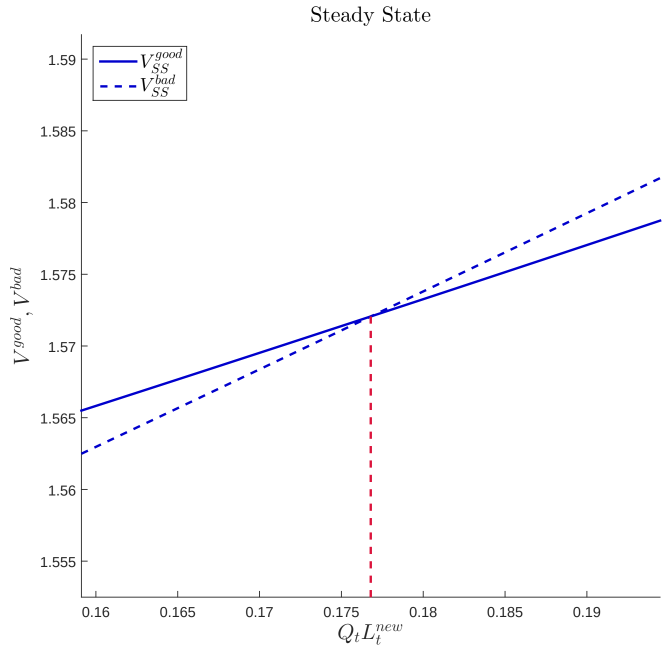

Figure 6: ***Credit Rationing.*** *Based on the calibration of the model as outlined in section 4.7, the objective functions V^{good} and V^{bad} are plotted against $Q_t L^{new}_t$. All state variables are at their stochastic steady state values and all endogenous variables are held constant while L^{new}_t is varied. The range of L^{new}_t is chosen to cover a three standard deviation of L^{new}_t from its steady state value (based on a simulation of the model).*

Proposition 1. *Since (7) is always binding, the solution to the entrepreneur's decision problem is given by L^{new*}_t where*

$$\begin{aligned} 0 &= \frac{K^{new}_t}{L^{new*}_t} J_t - G_t + \frac{L^{new*}_t}{K^{new}_t} S_t \\ Q^K_t K^{new}_t &= Q_t L^{new*}_t + N_t \end{aligned}$$

and J_t, G_t, and S_t are three 'forward-looking' auxiliary variables defined in Appendix A.2.

Proof: See Appendix A.1.

The relative movement of V^{good}_t and V^{bad}_t over the business cycle determines how collateralized new lending is. During a recession, when profits to capital are low and default thresholds high, the bad project becomes relatively more attractive to a new entrepreneur. The risk-shifting problem therefore becomes more severe and credit to new entrepreneurs is rationed, such that not only total new lending declines, but also the loan-to-collateral ratio on new lending. The opposite holds during a boom when profits are high, default thresholds are low, and the good project becomes relatively more attractive. This can also be understood by considering the extreme case that the entrepreneur never defaults. Then, the good project dominates the bad one since it offers a higher expected return and incentives to risk-shift vanish, easing up credit supply and raising loan-to-collateral ratios.

4.4 Financial Intermediary

The role of the representative financial intermediary is to transform short-term and riskless debt B_t into long-term and risky loans L_t, given out to entrepreneurs. The financial intermediary is perfectly diversified and invests into the whole market portfolio of loans L_t which is defined recursively and encompasses all outstanding loans

$$L_t = L_t^{new} + \gamma L_{t-1}$$

I assume that the financial intermediary values shareholders' flow utility of real dividends D_t, denoted by

$$U(D_t) = log\,(D_t)$$

Given the aggregate state variables $\mathbb{S}_t$, its outstanding debt and interest $B_{t-1}R_t$, and loans L_{t-1} from last period, the financial intermediary chooses new short-term debt B_t, loans L_t, and dividends D_t every period to maximize life-time shareholder utility, discounted at the rate β^F. Taking prices and interest rates as given, the financial intermediary solves

"Unconstrained Problem".

$$V\left(\mathbb{S}_t, B_{t-1}R_t, L_{t-1}\right) = \underset{D_t, L_t, B_t}{max} \left\{U(D_t) + \beta^F \mathbb{E}\left[V\left(\mathbb{S}_{t+1}, B_t R_{t+1}, L_t\right)\right]\right\}$$

subject to

$$\begin{aligned} D_t + Q_t L_t + B_{t-1}R_t &\leq B_t + R_t^L Q_{t-1} L_{t-1} \quad (8) \\ \mathbb{S}_{t+1} &= \Gamma(\mathbb{S}_t) \end{aligned}$$

where Q_t is the price and R_t^L the return per loan in period t. Constraint (8) is a budget constraint, stating that the amount of new debt B_t and the profits on last period's loans $R_t^L Q_{t-1} L_{t-1}$ have to cover at least the payout of dividends D_t, new loan investment $Q_t L_t$, and outstanding debt and interest $B_{t-1}R_t$. The above problem implies that the financial intermediary never raises equity, but always issues a positive amount of real dividends. This assumption is reasonable, given that the model is mainly used to analyze the boom period before a financial crisis occurs, during which intermediaries can retain earnings to build up their capital buffer, and the bust, during which it is difficult to raise equity. The solution to the intermediary's "Unconstrained Problem" is given by two intertemporal optimality conditions

$$\begin{aligned} \frac{1}{D_t} &= \beta^F \mathbb{E}\left[\frac{1}{D_{t+1}}\right] R_{t+1} \quad (9) \\ \frac{1}{D_t} &= \beta^F \mathbb{E}\left[\frac{1}{D_{t+1}} R_{t+1}^L\right] \end{aligned}$$

I define R_t^L to be the return on the whole market portfolio of loans which is given by

$$R_t^L = \frac{\gamma Q_t + (1-\gamma)\frac{1}{L_{t-1}}\left\{\sum_{j=1}^{\infty}\left(1-\Phi(\overline{\omega}_{t|t-j})\right)\gamma^{j-1}L_{t-j}^{new} + (1-\mu)\sum_{j=1}^{\infty}\left[\int_{1-b}^{\overline{\omega}_{t|t-j}} \omega R_t^K Q_{t-1}^K \gamma^{j-1} K_{t-j}^{new}\, d\Phi(\omega)\right]\right\}}{Q_{t-1}} \quad (10)$$

R_t^L captures both returns from non-maturing loans γQ_t, as well as returns from maturing loans across all vintages. The latter consist of repaid loans (the first term in the curly bracket) and the recovery from defaulted loans (the second term in the curly bracket). It seems to be rather difficult to account for all loans in the economy. There is an infinite number of outstanding loans with vintage-specific debt L_t^{new} and underlying collateral K_t^{new} and hence vintage-specific default thresholds $\overline{\omega}_{t|t-j} = \frac{L_{t-j}^{new}}{R_t^K Q_{t-1}^K K_{t-j}^{new}}$ in period t. However, it is not necessary to keep track of the whole distribution of loans, but three aggregate state variables can account for R_t^L. Proposition 2 formalizes this claim.

Proposition 2. *The aggregate state variables*

$$
\begin{aligned}
L_t &= L_t^{new} + \gamma L_{t-1} \\
K_t &= K_t^{new} + \gamma K_{t-1} \\
x_t &= \frac{(L_t^{new})^2}{K_t^{new}} + \gamma x_{t-1}
\end{aligned}
$$

can account for all outstanding loans L_t, their combined collateral K_t, and all vintage-specific loan-to-capital ratios via the auxiliary variable x_t. Given the return on capital and the price per loan Q_t in period t, the profits per loan $R_t^L Q_{t-1}$ can be expressed in terms of only these three aggregate state variables.

Proof: See Appendix A.1.

The auxiliary variable x_t takes an intuitive form. It accounts for all vintage-specific loan-to-capital ratios since it is updated with the loan-to-capital ratio $\frac{L_t^{new}}{K_t^{new}}$ of newly issued loans each period, weighted by the face value L_t^{new} of these loans. One can therefore interpret x_t as a *loan risk indicator*. Further, by dividing x_{t-1} by all outstanding loans L_{t-1} and current profits to capital $R_t^K Q_{t-1}^K$, one can derive a *weighted default threshold* of all outstanding loans

$$
\overline{\omega}_t \equiv \frac{x_{t-1}}{L_{t-1} R_t^K Q_{t-1}^K} = \sum_{k=1}^{\infty} \frac{\gamma^{k-1} L_{t-k}^{new}}{L_{t-1}} \overline{\omega}_{t|t-k}
$$

where $\frac{L_{t-k}^{new}\gamma^{k-1}}{L_{t-1}}$ for $k \in \{1, 2, ..., \infty\}$ is the remaining fraction of a vintage of loans relative to all outstanding loans and $\overline{\omega}_{t|t-k}$ for $k \in \{1, 2, ..., \infty\}$ is the default threshold for vintage $t-k$ in period t.

The model gives a realistic representation of the financial sector's balance sheet. Table (1) illustrates the time dependence of the intermediary's asset portfolio in period t and how it intuitively relates to the aggregate state variables L_t, K_t, and x_t. For each vintage of loans, the amount of outstanding loans, their remaining collateral, and their default threshold in period t are shown. For example, with respect to the vintage of loans issued in period $t-2$ an amount $\gamma^2 L_{t-2}^{new}$ remains outstanding in period t, backed by collateral $\gamma^2 K_{t-2}^{new}$, and the default threshold in period t for the maturing loans of this vintage is given by $\overline{\omega}_{t|t-2}$. Table (1) highlights that loans which were issued in the past are going to remain on the financial sector's balance sheet for a longer period of time and that the conditions under which a loan was initially issued in the past determines its payoff in the present.

Loans issued in period	t	$t-1$	$t-2$	$t-3$	...	*State Variable*
Loans outstanding in period t	L_t^{new}	γL_{t-1}^{new}	$\gamma^2 L_{t-2}^{new}$	$\gamma^3 L_{t-3}^{new}$	...	$\sum_{k=0}^{\infty} \gamma^k L_{t-k}^{new} = L_t$
Collateral remaining in period t	K_t^{new}	γK_{t-1}^{new}	$\gamma^2 K_{t-2}^{new}$	$\gamma^3 K_{t-3}^{new}$	...	$\sum_{k=0}^{\infty} \gamma^k K_{t-k}^{new} = K_t$
Default threshold in period t	-	$\overline{\omega}_{t\|t-1}$	$\overline{\omega}_{t\|t-2}$	$\overline{\omega}_{t\|t-3}$	...	$\sum_{k=0}^{\infty} \gamma^k \frac{(L_{t-k}^{new})^2}{K_{t-k}^{new}} = x_t$

Table 1: ***Balance Sheet Financial Intermediary.*** *Illustration of the financial intermediary's assets in period t.*

4.4.1 Occasional Financial Crises

Next, I introduce occasional financial crises into the above framework. A financial crisis is triggered if the intermediary's choices under the "Unconstrained Problem" are such that its market leverage $\frac{B_t}{Q_t L_t}$ in period t exceeds the threshold κ. If that is the case, the financial intermediary additionally faces the constraint

$$B_t \leq \tau(\mathbb{S}_t) \tag{11}$$

which states that the amount of new debt B_t cannot exceed an upper limit $\tau(\mathbb{S}_t)$. This upper limit is a function of aggregate state variables and the functional form is chosen such that the intermediary has less debt available compared to the unconstrained case (described in more detail in the calibration of the model). The debt constraint is taken as given by the financial intermediary and enters directly into its decision problem, such that the intermediary solves

"Constrained Problem".

$$V\left(\mathbb{S}_t, B_{t-1}R_t, L_{t-1}\right) = \underset{D_t, L_t, B_t}{max} \left\{U(D_t) + \beta^F \mathbb{E}\left[V\left(\mathbb{S}_{t+1}, B_t R_{t+1}, L_t\right)\right]\right\}$$

subject to

$$\begin{aligned} D_t + Q_t L_t + B_{t-1}R_t &\leq B_t + R_t^L Q_{t-1} L_{t-1} \\ B_t &\leq \tau(\mathbb{S}_t) \\ \mathbb{S}_{t+1} &= \Gamma(\mathbb{S}_t) \end{aligned} \tag{12}$$

The solution to the problem is given by the two intertemporal optimality conditions

$$\begin{aligned} \frac{1}{D_t} - \lambda_t &= \beta^F \mathbb{E}\left[\frac{1}{D_{t+1}}\right] R_{t+1} \\ \frac{1}{D_t} &= \beta^F \mathbb{E}\left[\frac{1}{D_{t+1}} R_{t+1}^L\right] \end{aligned} \tag{13}$$

where λ_t is the lagrange multiplier on the debt constraint in (12), which is positive if $\tau(\mathbb{S}_t)$ is sufficiently low and the intermediary is therefore funding-constrained. I define a financial crisis or a creditor run to be a period in which the financial intermediary's leverage under the "Unconstrained Problem" exceeds the threshold κ and the intermediary has to solve the "Constrained Problem" instead. Creditor runs are linked to the balance sheet of the financial intermediary since they only occur if the intermediary's unconstrained choices are such that its market leverage exceeds the threshold κ which is consistent with the mentioned empirical evidence by Gorton (1988). In order to ensure that a financial intermediary is not caught in a spiral of constant creditors runs, I further assume that creditor runs cannot occur for two consecutive periods. This assumption ensures stability of the model and is in line with the observation that creditor runs generally occur within a small time window.

4.4.2 Risk and Liquidity Premia

The two Euler equations in (13) can be combined to an arbitrage equation

$$\mathbb{E}\left[\beta^F \frac{D_t}{D_{t+1}} R^L_{t+1}\right] \quad = \quad \mathbb{E}\left[\beta^F \frac{D_t}{D_{t+1}}\right] R_{t+1} + \lambda_t D_t$$

Denote the stochastic discount factor $M_{t,t+1} = \beta^F \frac{D_t}{D_{t+1}}$ and excess returns $R^X_{t+1} = R^L_{t+1} - R_{t+1}$. The expected excess return can then be divided into a classic "risk-premium" and a second component which is termed a "liquidity premium"

$$\mathbb{E}\left[R^X_{t+1}\right] = \underbrace{\frac{\lambda_t D_t}{\mathbb{E}\left[M_{t,t+1}\right]}}_{\text{Liquidity Premium}} - \underbrace{\frac{Cov(M_{t,t+1}, R^X_{t+1})}{\mathbb{E}\left[M_{t,t+1}\right]}}_{\text{Risk Premium}} \tag{14}$$

If $\lambda_t > 0$, the intermediary is funding constrained and the liquidity premium is positive which raises the expected excess return. This is in line with the observation that expected excess returns are generally high when an economy experiences a financial crisis during which intermediaries are funding-constrained (Muir, 2014).

4.5 Capital Producers and Resource Constraint

Capital good producers undertake real investment. Given the price of capital Q^K_t, capital good producers maximize their profits by choosing the economy-wide units of investment I_t

$$\max_{I_t} \ \left\{Q^K_t I_t - \Phi\left(I_t, K_{t-1}\right)\right\}$$

subject to

$$\Phi(I_t, K_{t-1}) \quad = \quad I_t + \frac{\zeta}{2}\left(\frac{I_t - \delta K_{t-1}}{K_{t-1}}\right)^2 K_{t-1}$$

where $I_t = K_t - (1-\delta)K_{t-1}$ and $\Phi(I_t, K_{t-1})$ reflects quadratic adjustment costs which follows the parsimonious specification in He and Krishnamurthy (2014). The above problem gives the intratemporal optimality condition

$$Q_t^K = 1 + \zeta\left(\frac{I_t}{K_{t-1}} - \delta\right)$$

I complete the description of the real model by stating the resource constraint

$$Y_t = C_t + D_t + I_t + \frac{\zeta}{2}\left(\frac{I_t - \delta K_{t-1}}{K_{t-1}}\right)^2 K_{t-1} + (1-\gamma)\mu\sum_{j=1}^{\infty}\left[\int_{1-b}^{\overline{\omega}_{t|t-j}} \omega R_t^K Q_{t-1}^K \gamma^j K_{t-j}^{new} d\Phi(\omega)\right]$$

implying that the final output good is used as consumption, as conversion into capital goods, and for covering real default costs.

4.6 Equilibrium Conditions and Numerical Solution

Given the optimality conditions to the agents' decision problems and the clearing of goods, labor, and debt markets, the equilibrium conditions of the model for $t = 0, 1, ..., \infty$ are listed in Appendix A.2, given an initial state $\mathbb{S}_0$. The endogenous variables can be separated into a vector of non-state variables X_t and a vector of state variables $\mathbb{S}_t$. X_{t+1} is unknown in period t and $\mathbb{S}_t = \left\{\overline{S}_t, \hat{S}_t\right\}$ comprises both exogenous state variables $\overline{S}_t$ and endogenous state variables $\hat{S}_t$. $\overline{S}_t = \{\rho_a a_{t-1} + \epsilon_t^a\}$ includes the technology shock ϵ_t^a and the probability distribution of this shock is known to all agents. The realization ϵ_{t+1}^a is unknown in period t. $\hat{S}_t = \{K_{t-1}, L_{t-1}, x_{t-1}, R_t B_{t-1}, r_{t-1}\}$ collects the endogenous state variables and $\hat{S}_{t+1}$ is known in period t. Overall, the model has six state variables. One is linked to the shock, three arise from the defaultable loan contracts, K_{t-1}, L_{t-1}, and x_{t-1} (as defined in Proposition 2), $R_t B_{t-1}$ accounts for the outstanding debt of the financial intermediary, and r_{t-1} is an indicator variable which is equal to one if there has been a creditor run in the previous period and zero otherwise.

Definition 1. *A competitive general equilibrium is a solution of the model which is given by a set of policy functions* $\hat{S}_{t+1} = f_{\hat{S}}(\mathbb{S}_t)$ *and* $X_t = f_X(\mathbb{S}_t)$ *which satisfy the model's equilibrium conditions listed in Appendix* A.2 *for* $t = 0, 1, ..., \infty$ *in the relevant state space.*

Numerical methods are used to solve for the policy functions $f_{\hat{S}}(\mathbb{S}_t)$ and $f_X(\mathbb{S}_t)$. However, instead of relying on local perturbation methods which are commonly used to solve dynamic stochastic general equilibrium models, I solve the model using projection methods which give a global nonlinear solution of the model. I rely on such methods for two reasons. First, projection methods allow to integrate occasionally-binding constraints easily. Here, the amount of debt a financial intermediary can raise is occasionally constrained when a creditor run occurs. The intermediary's problem is therefore solved sequentially. In a first step, the "Unconstrained Problem" is solved and if the intermediary's leverage exceeds the threshold κ under this problem, the "Constrained Problem" is solved instead. And second, the solution method captures precautionary behavior by agents linked to whether a financial crisis may occur in the future due to the realization of future shocks. I give a detailed description of the solution algorithm in Appendix A.3.

4.7 Calibration

The model is calibrated to quarterly frequency for the U.S. economy. The structural parameters are listed in Table (2) and I discuss the calibration of the non-standard parameters next.

The persistence and standard deviation of the technology shock are obtained by estimating an AR(1) process to the linearly detrended utilitization-adjusted log-TFP-series by Fernald (2014) for the second half of the post-WWII period (1980Q1-2014Q2), giving $\rho_a = 0.93$ and $\sigma_a = 0.72\%$. The difference between the household's discount rate β^H and the financial intermediary's discount rate β^F determines the market leverage of the financial intermediary - the model's main indicator of financial stability. The literature tends to calibrate this difference to match an empirical counterpart for the intermediary's leverage. However, this approach

Agents	*Description*	*Parameter*	*Value*	*Target / Source*
Household	*Discount factor HH*	β^H	*0.99*	Literature
	Inv. Frisch elasticity	ϕ	*0.5*	Literature
	Rel. utility weight	χ	*1.6*	*Normalization:* $H \sim 1$ *in steady state*
Good Producer	*Effective capital share*	α	*0.3*	Literature
	Depreciation rate	δ	*0.025*	Literature
	Std. technology shock	σ_a	*0.72%*	*Util.-adj. TFP series (Fernald, 2014)*
	Persist. technology shock	ρ_a	*0.93*	*Util.-adj. TFP series (Fernald, 2014)*
Intermediary	*Discount factor FI*	β^F	*0.987*	*Impulse response matching*
	Leverage threshold	κ	*0.49*	*Frequency Crises:* $\sim$ *2.4%*
	Debt constraint	$\overline{\tau}$	*0.91*	*Severity Crises* $: \frac{\Delta GDP\ Fin.Rec.}{\Delta GDP\ Ave.Rec.} \sim 1.12$
				Boissay, Collard and Smets (2013, 2015)
Entrepreneurs	*Width support of* ω	b	*1*	$\sigma^2_\omega = \frac{1}{3}$ *, BGG (1999)*
	Mean of $\widetilde{\omega}$	$\widetilde{k}$	*0.9*	$E_t[R^L_{t+1}] < 1\ \forall\ t$ *under bad project*
	Width support of $\widetilde{\omega}$	$\widetilde{c}$	*1.55*	*Annual Default Rate* $\sim 3\%$
	Default costs	μ	*0.12*	*Bernanke, Gertler and Gilchrist (1999)*
	Stochastic maturity loan	γ	*0.908*	*Mat. Mismatch U.S. Comm. Banks*
Capital Producer	*Capital adjustment cost*	ζ	*3*	*He and Krishnamurthy (2014)*

Table 2: ***Calibration.*** *Calibration of structural parameters.*

faces the challenge that the financial intermediary sector is a very heterogeneous sector, encompassing for example hedge funds, commercial banks, and investment banks. Such financial institutions show quite distinct leverage ratios. It is therefore a challenge to find a one-size-fits-all-calibration. Moreover, besides the overall level of leverage, what is particularly important is how leverage behaves over the business cycle, as emphasized in the work of Adrian and Shin (2010), which in the end determines how the economy transits from a standard business cycle period into a financial crisis. In this regard, the impulse response of leverage to the model's aggregate source of risk (the technology shock) governs how financial stability and aggregate risk interact and is crucial for the results which follow. I therefore obtain empirical evidence in this respect and match the model's implied impulse response to this evidence by choosing the difference between β^H and β^F. The intuition behind this calibration approach is that the difference between β^H and β^F not only determines the overall level of leverage, but also the shape of the impulse response of leverage. The larger the gap between β^H and β^F, the higher the intermediary's leverage. Moreover, the higher the initial leverage, the more strongly leverage increases after an adverse shock which decreases the value of assets. And, after an adverse shock which decreases the value of assets, it also takes longer for leverage to reach again its initial level the more leveraged the intermediary is, given constraints which prevent the sector from deleveraging quickly (such as restrictions on raising equity in the short run). Hence, by choosing the difference between β^H and β^F, both level and impulse response of leverage are determined.[9]

The residual of the estimated AR(1) process for the utilization-adjusted TFP series gives a quarterly series of structural technology shocks $\{\hat{\epsilon}_t^a\}$ from 1980Q1 to 2014Q2. Based on the derived measure of U.S. financial sector's market leverage in this chapter (see Appendix A.9 for details), an impulse response function of market leverage $\widehat{Lev}_t$ to this shock series is obtained with a version of the method of local projections similar to Jordà (2005).[10,11] Using the generalized method of moments (GMM), I simultaneously estimate the following system[12,13]

$$log(TFP)_t = \alpha_0 + \rho_a log(TFP)_{t-1} + \hat{\epsilon}_t^a \tag{15}$$

$$\widehat{Lev}_{t-1+k} - \widehat{Lev}_{t-1} = \beta_0^k + \beta_1^k \hat{\epsilon}_t^a + e_{t+k} \quad for \;\; k \in \{1, 2, ..., 20\} \tag{16}$$

[9]It should be noted that this calibration approach differs from Christiano, Eichenbaum and Evans (2005) in two respects. First, Christiano, Eichenbaum and Evans (2005) estimate their model to minimize the distance between VAR and model responses to a monetary policy shock. Here, the fact that the model is solved globally complicates such an exercise and therefore the difference between β^H and β^F is calibrated to roughly match the initial sign and turning point of the empirical impulse response. Second, Christiano, Eichenbaum and Evans (2005) aim to match impulse responses of standard macroeconomic variables. Here, the impulse response of leverage is targeted which relates financial stability and aggregate risk.

[10]As in Figure (1), I use data on commercial and investment banks. See Appendix A.9 for a description of the data and derivations.

[11]See Romer and Romer (2004) for a similar method to obtain impulse response functions.

[12]GMM requires the choice of a weighting matrix and instruments. Regarding the weighting matrix, a Newey-West correction for heteroscedasticity and autocorrelation is used. The instruments are the regressors in (15) and (16).

[13]The system is estimated jointly in order to avoid a generated regressor problem. Such a problem arises when estimating the series $\{\hat{\epsilon}_t^a\}$ first and then using this series to derive impulse response functions. Newey and McFadden (1994) show that one can obtain consistent estimates by simultaneously estimating all equations, using GMM.

where β_1^k gives the reaction of leverage to a technology shock at horizon k.[14] The coefficients are normalized to the obtained standard deviation $\sigma_a = 0.72\%$ and the result is shown in Figure (7) for which the standard error of β_1^k at horizon k is used to obtain the confidence bands. Following a positive technology shock, leverage initially declines and then rises over time, turning positive after around eight quarters.[15] By calibrating β^F for a given β^H, I find that an asset-to-equity ratio of around 2 gives a model implied impulse response that matches well the initial sign and the turning-point of the obtained empirical impulse response. This calibration gives a slightly lower leverage than observed among commercial and investment banks, which operate under asset-to-equity ratios above 5 in normal times, but matches well with other parts of the intermediary sector - such as hedge funds which show ratios of around 2 (Ang, Gorovyy and van Inwegen, 2011).

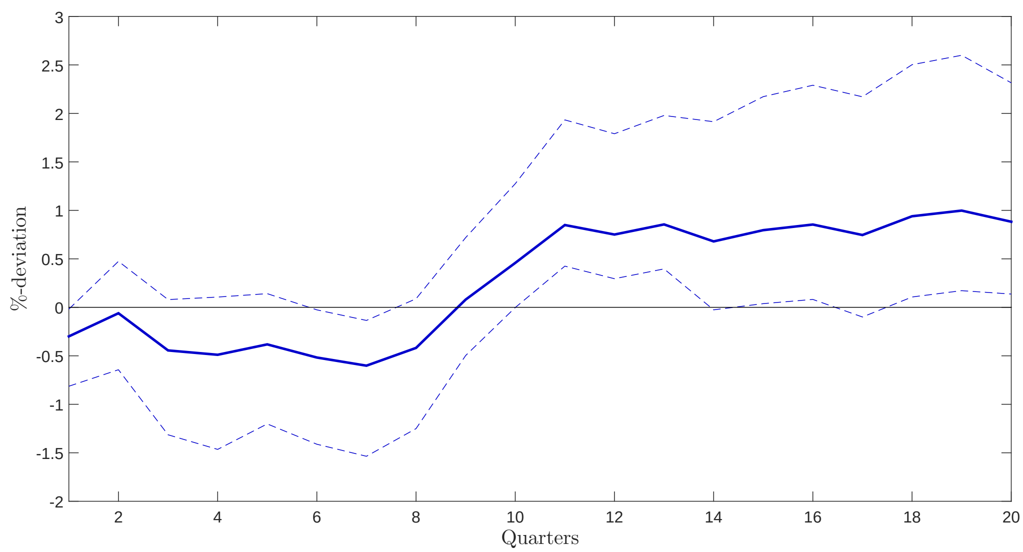

Figure 7: ***Impulse Response Function.*** *IRF of market leverage to a one standard deviation positive technology shock. 95% confidence bands shown. Regarding the market leverage of the financial sector, see Appendix A.9 for a description of the data and calculations.*

[14] In (16), $\widehat{Lev}_{t-1}$ and β_0^k are used as a proxy for the path that leverage would have followed in the absence of a shock $E_{t-1}\left[\widehat{Lev}_{t-1+k}\right]$. The results are robust to controlling for additional lags of leverage. Given the limited length of the time series, up to three lags are included in this robustness check. These additional results are not reported, but are available upon request.

[15] Using the specification in (16), I confirm that the initial decline in market leverage after a positive technology shock is due to an immediate increase in the market equity of financial institutions, whereas book values respond more slowly. Moreover, real GDP increases following a positive technology shock. These results are in line with the model's impulse responses presented in section 4.8 and are available upon request.

The leverage threshold κ governs the frequency of crises in the model and I choose κ to match an annual frequency of around 2.4%, based on calculations in Boissay, Collard and Smets (2015).[16] When a creditor run occurs, a financial intermediary is restricted in the amount of new debt B_t to raise. According to equation (11), the financial intermediary cannot take on more new debt than $\tau(\mathbb{S}_t)$. I choose $\tau(\mathbb{S}_t)$ such that the intermediary is always able to repay its outstanding debt, but has less new debt B_t available to finance dividend payouts and newly issued loans compared to its unconstrained choices, i.e.

$$\tau(\mathbb{S}_t) = \overline{\tau}\,(D_t^{unc} + Q_t^{unc} L_t^{new,unc}) + B_{t-1}R_t - R_t^L Q_{t-1} L_{t-1} + Q_t \gamma L_{t-1}$$

where the superscript *unc* describes the intermediary's choices under the "Unconstrained Problem". The parameter $0 < \overline{\tau} < 1$ determines the severity of a financial crisis. Boissay, Collard and Smets (2013) show that for 14 OECD countries the drop in real GDP from peak to trough is around 11.8% bigger during financial recessions (-6.61%) than during average recessions (-5.91%) based on HP-filtered data. I choose $\overline{\tau}$ such that the ratio between financial and average recessions in a simulation of the model matches this empirical finding, giving $\overline{\tau} = 0.91$.[17]

The following parameters govern the long-term debt contract between the financial intermediary and entrepreneurs. The parameter b controls the variance of the idiosyncratic shock ω, received by an entrepreneur with a maturing loan on its profits. I choose $b = 1$ which is convenient as it gives a lower bound of zero on the idiosyncratic shock and therefore ensures that the default thresholds are always above this lower bound. Given $b = 1$, the variance of the idiosyncratic shock is $\frac{1}{3}$ which is close to the variance of the idiosyncratic shock of 0.28 as chosen by Bernanke, Gertler and Gilchrist (1999). The mean and the variance of the id-

[16]The data and calculations by Schularick and Taylor (2012) and Boissay, Collard and Smets (2015) are based on an annual frequency. In order to ensure consistency, the following definition is used. A year in which at least one financial crisis occurs is counted as one "financial-crisis-year". Given this definition, an annual frequency of around 2.4% is targeted.

[17]Following Boissay, Collard and Smets (2013), I define a recession as a year in which the percentage change in output is among the 10.2% lowest changes, from the peak of the previous year to the trough of the current year, which is consistent with the fact that recessions are observed around 10.2% of the time in the data. A recession during which a creditor run occurs is defined as a financial recession and a recession during which no creditor run occurs is defined as a non-financial recession.

iosyncratic shock $\widetilde{\omega}$ under the bad project are chosen to match two targets: an annual default rate of around 3% in steady state (as in Bernanke, Gertler and Gilchrist, 1999) and to ensure that the financial intermediary prefers not to lend to entrepreneurs who invest in the bad project, because the expected return on such an investment is below one and therefore implies a negative net present value investment for the intermediary. The fraction of profits which is lost in case of default μ is directly taken from Bernanke, Gertler and Gilchrist (1999) and set to 0.12. English, van den Heuvel and Zakrajsek (2012) document that the average maturity of assets of U.S. commercial banks is around 4.5 years, of liabilities around 0.4 years, with a ratio between the two of 10.88. I normalize the maturity of short-term debt to one quarter and choose γ to give an average maturity of long-term debt of 10.88 quarters. The stochastic steady state resulting from this calibration is given in Appendix A.5 and the accuracy of the solution is shown in Appendix A.4. Next, I analyze the dynamics of the model with respect to the technology shock.

4.8 Impulse Response Functions

Figures (8) and (9) show impulse response functions to a one standard deviation positive technology shock, starting from the stochastic steady state of the model. For these responses, a financial crisis does not occur as the intermediary's leverage is sufficiently below the threshold κ. Following a positive technology shock, output Y_t and consumption C_t increase. And due to consumption smoothing and the increase in the real wage, the household's savings increase, the real interest rate R_{t+1} declines, and the household chooses to work more, such that H_t increases. After a positive technology shock, the profits to capital $R_t^K Q_{t-1}^K$ increase which decreases the probability of default of all outstanding loans as indicated by the weighted default threshold $\overline{\omega}_t$. Since new entrepreneurs are also less likely to risk-shift, they can borrow more in absolute terms, $Q_t L_t^{new}$, in relative terms to their collateral $\frac{L_t^{new}}{K_t^{new}}$, and the face value of their loans L_t^{new} increases. The loan risk indicator x_t therefore rises.

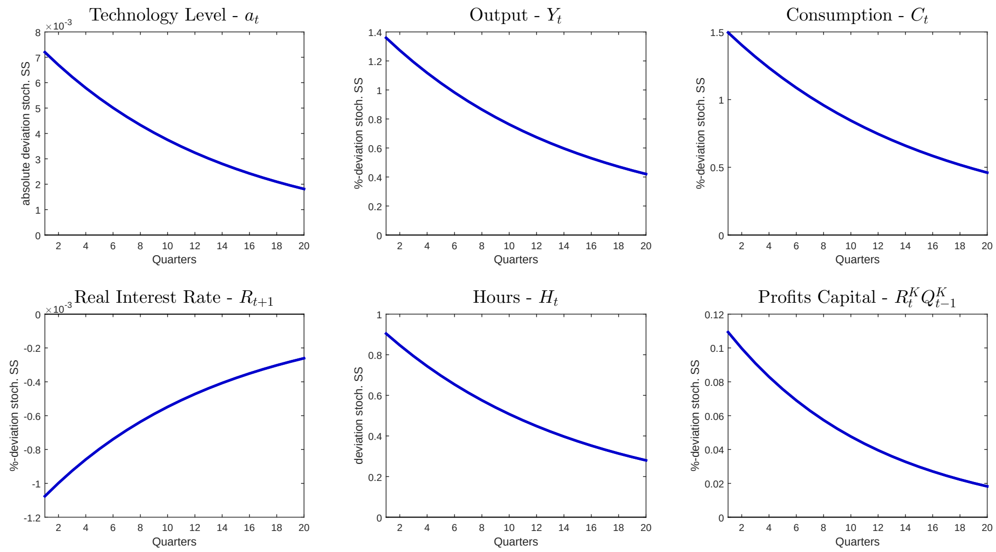

Figure 8: ***Impulse Response Functions.*** *IRFs to a one standard deviation positive technology shock, starting at stochastic steady state of the model.*

Following a positive technology shock, the financial intermediary expands its balance sheet. Given the reduced incentives to risk-shift and the lower real interest rate, the intermediary takes on more debt B_t to increase its new lending. The overall stock of outstanding loans L_t and the economy's capital stock K_t therefore rise. The lower real interest rate and the increased profitability of its loan portfolio, $R_t^L Q_{t-1}$, induce the intermediary to pay out more dividends D_t. The intermediary's market leverage $\frac{B_t}{Q_t L_t}$ initially decreases since all of its loans are increasing in value. Over time, when the price of loans Q_t returns and the intermediary continues to take on more debt to issue new loans, its market leverage increases. The impulse response of leverage therefore roughly matches the empirical impulse response shown in Figure (7) - with the difference that the initial decline in the model is stronger than in the data.

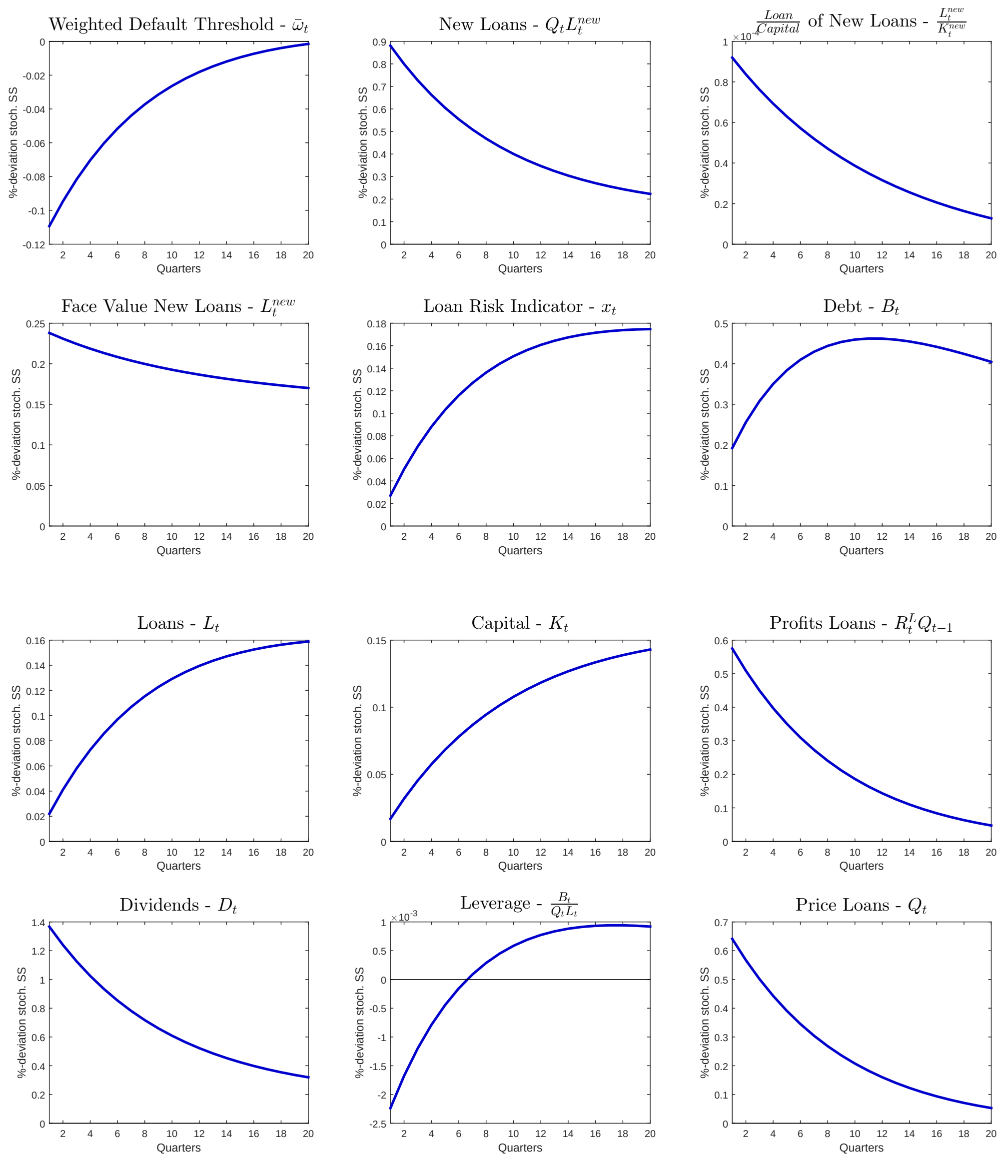

Figure 9: ***Impulse Response Functions.*** *IRFs to a one standard deviation positive technology shock, starting at stochastic steady state of the model.*

4.9 Financial Crises

In principle, a financial crisis can break out at any point in time if an adverse technology shock is sufficiently large. Hence, nothing in the model restricts crises to occur out of booms or recessions. However, financial crises are more likely to happen if certain preconditions are met. In order to understand these preconditions, I analyze the typical behavior of endogenous variables and the aggregate shock around financial crises. First, the model is simulated for 500,000 periods. Then, I collect the sequences of endogenous variables and shocks in a window of 30 quarters before and 20 quarters after a financial crisis. Figures (10) and (11) plot period by period the median, 33rd, and 66th percentile across these sequences for each variable with respect to windows in which only one financial crisis occurs. In what follows, the median path for each variable is referred to as the "typical path" around a crisis.[18]

The first row in Figure (11) shows the typical behavior of the technology shock ϵ_t^a and the technology level a_t. A typical build-up period leading to a financial crisis is characterized by an elevated technology level. When the technology level starts to decline, the probability that a crisis will occur in the next quarter has already started to increase. A typical crisis is initiated by a relatively moderate adverse change in the technology level which occurs within a one-year window. After the first adverse changes in the technology level, the probability that a crisis will occur within the next quarter strongly increases. The median shock which triggers a crisis is a negative 1.58 standard deviation shock. Typical financial crises therefore occur out of boom periods and the model does not need to rely on extremely large adverse shocks in order to initiate financial crises.

Output Y_t, the capital stock K_t, and hours H_t all increase in the build-up period and decrease once a crisis is triggered. Additionally, the model depicts an endogenous credit risk cycle. A lending boom occurs before a typical crisis as more loans $Q_t L_t^{new}$ with higher loan-to-capital ratios $\frac{L_t^{new}}{K_t^{new}}$ are issued which are both strongly decreasing in the bust. The overall stock of loans L_t and the loan risk indicator x_t therefore increase in the boom and over time

[18] The median path does not necessarily represent the path around one particular crisis. In order to give an example of a path around one particular crisis, in Appendix A.6 the behavior of variables around the crisis is reported, for which the shock sequence preceding a crisis is closest to the median shock sequence in Figure (10). This exercise is in the spirit of Fry and Pagan (2011) with respect to the literature on sign restrictions. However, the motivation for conducting this exercise is different. Fry and Pagan (2011) suggest to report the impulse responses of the model which is closest to the median impulse response, which is obtained across a range of models, since the median impulse response does not imply the identification of one unique model. Fry and Pagan (2011) term this suggested impulse response the median target response. In contrast, here, the model is identified, but the paths leading to financial crises can take different shapes, based on a simulation of the model. The "median target financial crisis" is reported to give an example of one particular path.

more risky loans accumulate on the intermediary's balance sheet.[19] Whereas the weighted default threshold $\overline{\omega}_t$ on all outstanding loans decreases in the boom, this trend is quickly reversed in the bust, when the intermediary suddenly holds a portfolio of non-performing loans and current and future default probabilities sharply increase.

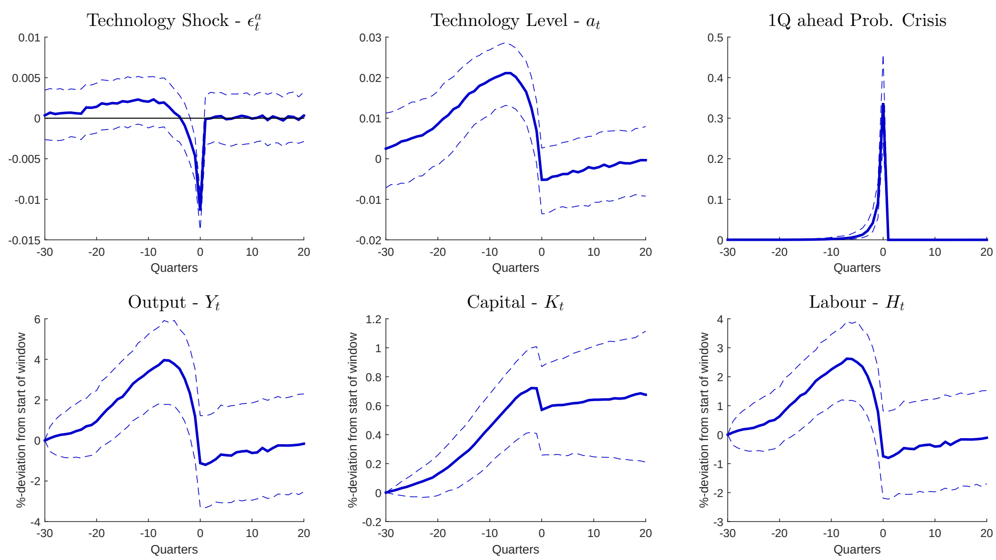

Figure 10: ***Typical Financial Crises.*** *Event window around financial crisis at Quarter = 0. Based on a simulation of 500,000 periods. Median, 33rd, and 66th percentiles are shown.*

The financial intermediary sees its profits on loans $R_t^L Q_{t-1}$ rise in the boom and pays out more dividends D_t. As the household smooths consumption by saving in the boom period, the real interest rate R_{t+1} declines. The decline in the interest rate and the easing of the risk-shifting problem induce the intermediary to expand its balance sheet by taking on more debt B_t to issue more loans. The intermediary's market leverage $\frac{B_t}{Q_t L_t}$ increases slowly in the boom and then sharply spikes during the crisis, which is consistent with the data shown in Figure (1).

The path of leverage is linked to the impulse responses shown in the last section. During a prolonged boom, the medium-term response of leverage to a positive technology shock dominates and leverage slowly increases following a persistently elevated technology level. In

[19]Based on the simulation of the model, Appendix A.8 replicates the baseline regressions in Schularick and Taylor (2012) and confirms their result that credit expands prior to financial crises.

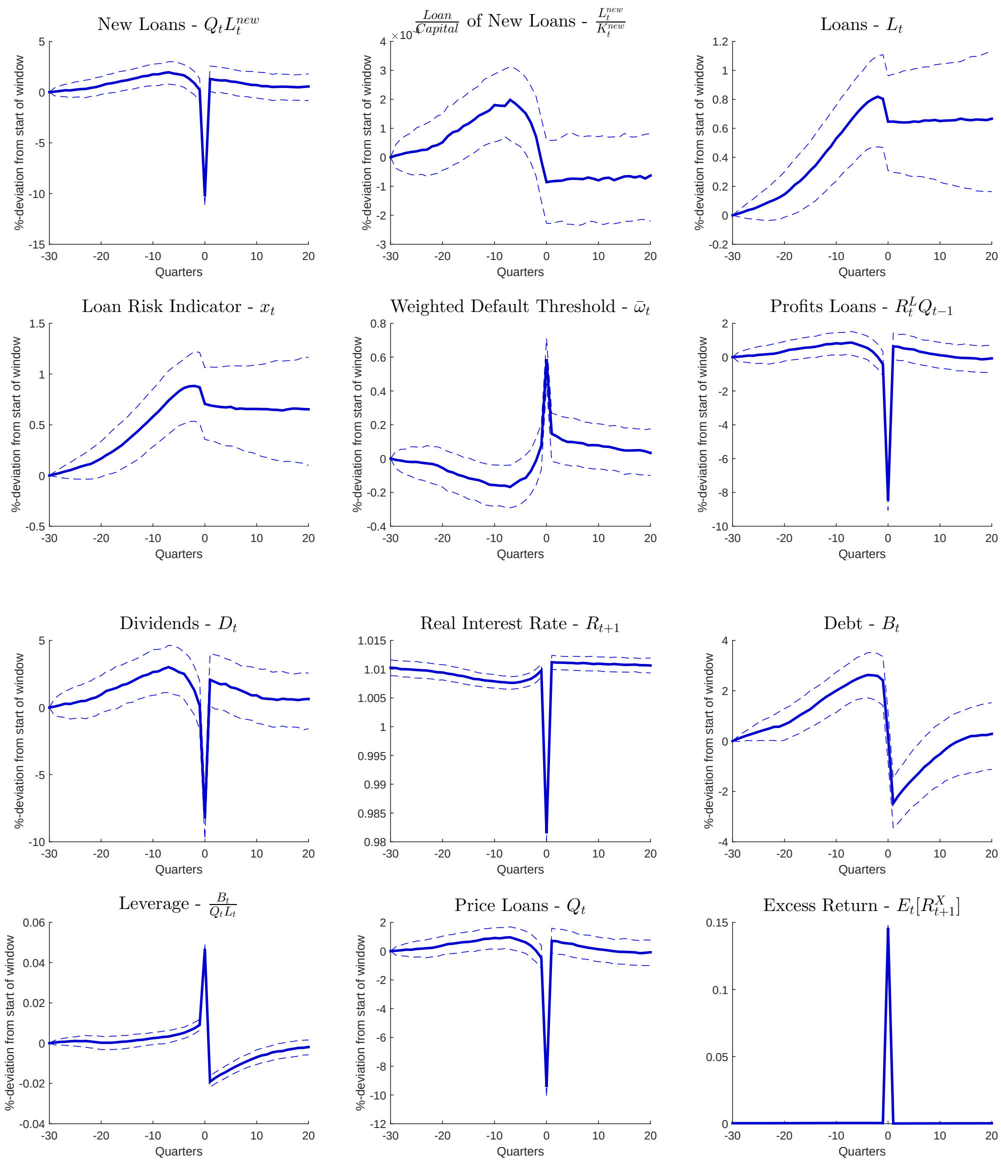

Figure 11: ***Typical Financial Crises.*** *Event window around financial crisis at Quarter = 0. Based on a simulation of 500,000 periods. Median, 33rd, and 66th percentiles are shown.*

a bust, the short-run response of leverage dominates and leverage increases following a negative technology shock. The rise of leverage in the bust is due to the drop in the value of the whole market portfolio of loans, while the intermediary still has to service its increased debt burden. The intermediary cannot deleverage by raising equity or by selling its assets to an outsider. Hence, the financial sector is unable to restructure its balance sheet quickly and holds a portfolio of non-performing loans during a crisis. The combination of these effects leads to an increase in the intermediary's leverage above the threshold κ under the "Unconstrained Problem" and creditors run. A creditor run further amplifies the initial increase in leverage since the value of loans Q_t drops even more when the intermediary is funding-constrained - resulting in a sharp spike of leverage during a crisis. Further, the risk-free interest rate R_{t+1} drops during a crisis due to the quantity-restriction in the short-term debt market associated with a creditor run. While the intermediary is funding-constrained, the expected excess return $\mathbb{E}\left[R^X_{t+1}\right]$ sharply increases due to a positive "liquidity-premium" as shown in equation (14) which is consistent with empirical evidence (Muir, 2014).

Besides playing a key role during a financial crisis when the financial sector finds itself with a portfolio of non-performing long-term loans, the maturity mismatch is also important for understanding the build-up period. The longer the boom lasts, the more old, maturing loans are replaced by new loans backed by less collateral and therefore the stronger the expansion of the intermediary's balance sheet and leverage. Due to the maturity mismatch, this process takes some time - a financial sector cannot change the structure of its balance sheet quickly and a typical crisis does not build up over night.

4.10 Non-Financial Recessions

In order to understand how financial crises differ from non-financial recessions (defined in footnote 17), I repeat the exercise of the last section around non-financial recessions. Figures (28), (29) and (30) in Appendix A.7 plot the typical median paths around non-financial recessions and financial crises. Compared to financial crises, the rise and decline in output associated with non-financial recessions is less pronounced. In line with the findings on financial crises, non-financial recessions are triggered by a relatively moderate adverse shock. The median shock which triggers a crisis is a 1.61 standard deviation negative technology shock. Compared to financial recessions, the role played by the financial sector is quite different with respect to non-financial recessions. Non-financial recessions are not preceded by strong increases in credit L_t, the intermediary's debt B_t, market leverage $\frac{B_t}{Q_t L_t}$, or the loan risk indicator x_t, which contrasts the behavior of these variables in the build-up towards financial crises. During non-financial recessions, the weighted default threshold $\overline{\omega}_t$, the intermediary's market leverage, and the expected excess return $\mathbb{E}\left[R^X_{t+1}\right]$ do not sharply increase as during financial crises. Further, the drop in the intermediary's funding B_t, its dividend payout D_t, new loans $Q_t L_t^{new}$, loan-to-capital ratios $\frac{L_t^{new}}{K_t^{new}}$, and the value of loans Q_t are stronger during financial crises. Overall, this comparison shows that it is the *financial sector's balance sheet* and its *lending behavior* which play crucial roles during the boom-bust cycle around financial crises. In this regard, non-financial recessions are different.

4.11 Predicting Financial Crises

How well does the model perform in predicting and replicating financial crises that were observed ex-post? In order to test the model in this regard, I again obtain a historical series of structural technology shocks $\{\hat{\epsilon}^a_t\}$, given the estimated AR(1) process to the utilitization-adjusted TFP-series by Fernald (2014), and feed the model with this series.

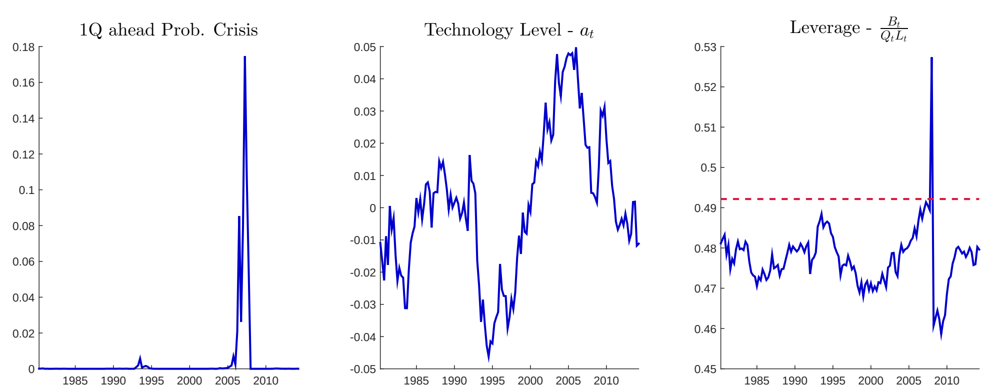

Figure 12: ***Predicting Financial Crises.*** *Model implied variables, given structural series of technology shocks $\{\hat{\epsilon}^a_t\}$. Red, dotted line indicates the threshold level of leverage κ, above which a creditor run occurs.*

The result is shown in Figure (12) which plots the path of the technology level a_t, the probability that a financial crisis will occur in the next quarter, and the path of the intermediary's market leverage $\frac{B_t}{Q_t L_t}$. During the boom period of 2000 to 2005, the technology level increases step-by-step and so does the intermediary's leverage. This boom period is followed by declines in the technology level which initiate a crisis and lead to a creditor run when the intermediary's leverage goes beyond the threshold κ (indicated by the red, dotted line). While the probability that a crisis will occur during the next quarter remains close to zero for most of the sample, it starts to increase around 2005 and jumps up in the quarters that follow. Hence, even though the information that is given to the model is quite limited, the model does a remarkable job in predicting the Great Recession and replicating the occurrence of a financial crisis in 2008Q3.

4.12 Book Leverage

Besides defining leverage at market values, the framework also allows to derive a measure of *book leverage*

$$\text{Market Leverage} \equiv \frac{B_t}{Q_t L_t} \qquad \text{Book Leverage} \equiv \frac{B_t}{BA_t} \tag{17}$$

where BA_t stands for *book assets*, defined recursively

$$BA_t = Q_t L_t^{new} + \gamma BA_{t-1} \tag{18}$$

such that newly issued loans are recorded on the balance sheet with the value at which they were given out and held constant until they mature.

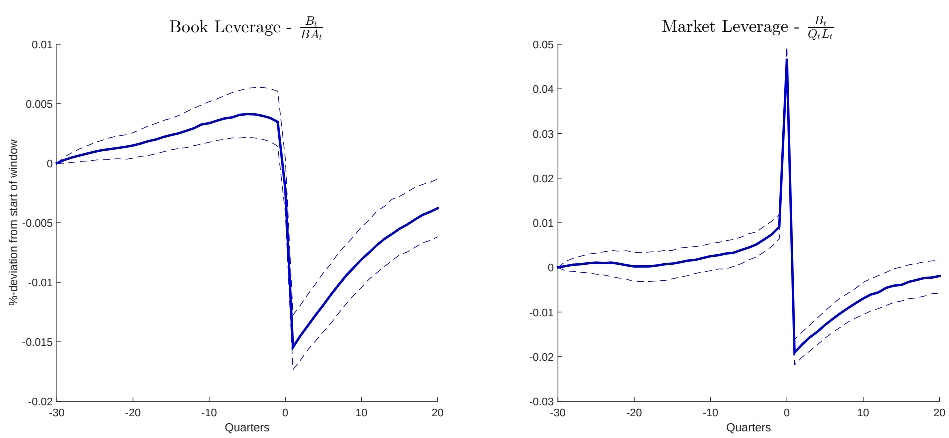

Figure 13: ***Book vs. Market Leverage around Financial Crises.*** *Event window around financial crisis at Quarter = 0. Based on a simulation of 500,000 periods. Median, 33rd, and 66th percentiles are shown.*

Given definitions (17) and (18), the typical behavior of book leverage around financial crises based on the simulation of the model is shown in Figure (13) - comparing it to the behavior of market leverage. While market leverage increases mildly prior and sharply during a crisis, book leverage rises in the run-up and decreases during a crisis. The different behavior of the two measures is due to the distinct valuation of outstanding loans. Market leverage increases less during the build-up period because outstanding loans are valued at current, rising market prices - lowering leverage - while they are held constant using the measure of book leverage. The strong increase in market leverage during a crisis is due to the fall in the value of all outstanding loans, which are held constant given definition (18) and book leverage decreases instead during a crisis.

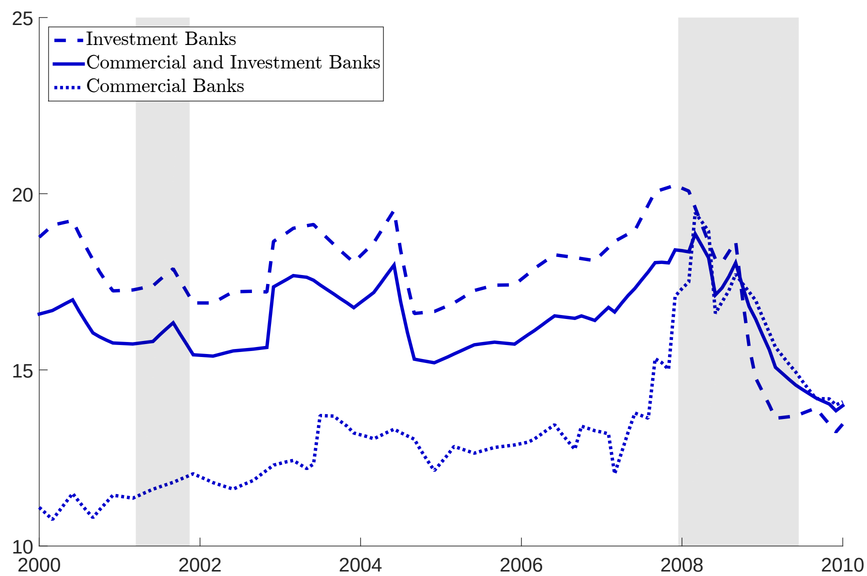

Figure 14: ***Book Leverage around the Great Recession.*** *The graph shows the evolution of book leverage around the Great Recession (total book assets / (total book assets - total book liabilities)), differentiating between types of U.S. financial institutions. See Appendix A.9 for a description of the data and derivations. Grey bars denote NBER recessions.*

The behavior of book and market leverage around financial crises are consistent with their empirical counterparts. As mentioned, market leverage matches the empirical measure shown in Figure (1). Figure (14) additionally shows the behavior of book leverage around the Great

Recession (see Appendix A.9 for a description of the data). In line with the behavior in the model, book leverage increased from around late 2004 and decreased during the crisis.

Market leverage also outperforms book leverage as an indicator of financial crises. In a regression with the probability that a crisis will occur in the next period as the dependent variable, both measures are significant, but market leverage explains are larger amount of the variation in the crisis probability. The results are reported in Table (3).[20]

	OLS	OLS
	Market Leverage	Book Leverage
R^2	0.24	0.04
F-Test (%)	0.00	0.00

Table 3: ***Indicators of Financial Crises.*** *The dependent variable is the probability that a crisis will occur in the next period, based on a simulation of 500,000 periods of the model. The regressors are market and book leverage.*

4.13 Cyclicality of Leverage

Book and market leverage do not only behave differently around financial crises, but also over the business cycle. Starting with the work of Adrian and Shin (2010), the cyclicality of financial institutions' leverage has been discussed as an indicator of the financial sector's procyclical risk-taking. Adrian and Shin (2010) show that leverage of certain financial institutions is procyclical based on book value data. These results are confirmed in Table (5). Based on a measure of book leverage (see Appendix A.9 for details), the correlation between leverage and real GDP is obtained.[21] Two samples are considered, one including and one excluding the Great Recession. Book leverage is procyclical and significant at the 1% confidence level for the sample *1980Q1-2014Q2*. The model's implied cyclicality of book leverage is in line with this empirical evidence. Based on a simulation of the model, the correlation between output Y_t and book leverage $\frac{B_t}{BA_t}$ is 0.49.

[20]However, both measures of leverage outperform any of the model's aggregate state variables which explain an even lower amount of the variation in the crisis probability.

[21]Logged GDP and leverage are detrended using a Hodrick-Prescott-Filter (a smoothing parameter of 1600 for quarterly data is applied following Ravn and Uhlig, 2002).

	1980Q1-2007Q4	*1980Q1-2014Q2*
Real GDP	0.28 (0.2464)	0.38 *** (0.0063)

Table 4: ***Cyclicality Book Leverage.*** *Correlation between book leverage and GDP. Asterisks denote statistical significance at the 1%[***], 5%[**], and 10%[*] confidence level for testing the hypothesis of no correlation against the alternative of non-zero correlation. P-values are in parenthesis.*

The exercise is repeated using the measure of market leverage in this chapter (see Appendix A.9 for details) and reported in Table (5). Market leverage is mildly countercyclical. However, the hypothesis of a zero correlation cannot be rejected. The model's implied cyclicality of market leverage is in line with this empirical evidence. Based on a simulation of 500,000 periods, the correlation between output Y_t and leverage $\frac{B_t}{Q_t L_t}$ is close to zero (0.001).

	1980Q1-2007Q4	*1980Q1-2014Q2*
Real GDP	-0.03 (0.7210)	-0.12 (0.1439)

Table 5: ***Cyclicality Market Leverage.*** *Correlation between market leverage and GDP. Asterisks denote statistical significance at the 1%[***], 5%[**], and 10%[*] confidence level for testing the hypothesis of no correlation against the alternative of non-zero correlation. P-values are in parenthesis.*

This acyclicality of market leverage can be understood from the impulse response of leverage and output following a technology shock as shown in Figures (8) and (9). After a positive technology shock, output Y_t increases, while leverage decreases in the short run. In the medium run, leverage increases, while output is still above its steady state value. Output and leverage are therefore negatively correlated in the short run, but positively correlated in the medium run - explaining the overall correlation which is close to zero. However, the initial negative response of leverage after a positive technology shock does not imply that leverage decreases during a prolonged boom. As shown in Figure (11), following a *prolonged elevated technology level*, leverage slightly increases as the medium-term impulse response of leverage dominates the short-run response.

4.14 Extension: Nominal Model

The real version of the model outlined so far takes a simplified view of the economy in the sense that all debt contracts are written in real terms and monetary policy would be neutral. In Appendix B, I extend the model to include price rigidities, nominal debt contracts, and monetary policy. Monetary policy is non-neutral for two reasons. First, goods producing firms are subject to price stickiness (see for example Nakamura and Steinsson, 2008, for micro-data evidence on price-rigidities). Second, debt contracts are written in nominal terms. Changes to inflation therefore adjust the real burden of debt which has real effects on output under default and default costs (as in Gomes, Jermann and Schmid, 2014).

In a quantitative analysis of the model, I turn off the technology shock and the only aggregate disturbance is a monetary policy shock. This version of the model allows to study the impact of monetary policy on financial stability. The main findings are as follows. Financial crises still occur out of (credit) boom periods and are initiated by a relatively moderate adverse shock. Both expansionary and contractionary monetary policy can increase financial instability. Financial crises are most likely to be preceded by longer periods of expansionary monetary policy, followed by contractionary monetary policy. Thus, the typical pattern of the policy target rate which is most likely to adversely affect financial stability has a U-shaped form. The nominal interest rate therefore takes a similar path as the counterparts in the U.S. and in Japan prior their recent financial crises.

However, the increases in the policy target which initiate a financial crisis in the model are larger than the step-by-step increases prior to the recent financial crises in Japan and in the U.S. The model therefore offers a reason why central banks increase their target rate only in small steps. Larger changes put too much pressure on financial institutions' balance sheets. Nevertheless, the analysis shows that even small increases in the policy target can pressure financial institutions' balance sheet in the short run. Hence, a trade-off between price and financial stability may therefore arise during boom periods, when rising prices are pressuring the economy, but increases in the nominal interest rate may also increase financial instability in the short run. Moreover, since periods of low interest rates intensify the adverse impact of contractionary monetary policy on financial stability, they should be avoided by central banks if financial stability concerns outweigh other motives.

5 Conclusion

This chapter develops a calibrated macroeconomic model which includes financial intermediation and endogenous financial crises. The chapter presents a mechanism for how financial crises can occur out of boom periods and why they can be initiated by relatively moderate adverse shocks. The financial sector's balance sheet and its lending behavior play key roles in this regard. Financial crises occur out of boom periods because during good times, financial institutions expand their balance sheets. They take on more debt to issue loans which are backed by less collateral, as agency problems between the financial sector and its borrowers are relaxed in good times, and slowly increase their market leverage. After a sudden bust, current and future default probabilities of loans strongly increase, the financial sector holds a portfolio of non-performing loans, and is left with an increased debt burden. These effects pressure the financial sector's balance sheet, sharply increase its market leverage, and lead to a rationing of credit to intermediaries. The behavior of the financial sector's book and market leverage is consistent with the data - both around financial crises and over the business cycle.

Moreover, financial crises are rare events, break out in the midst of a credit-intensive boom, and are more severe than non-financial recessions. The model behaves differently around the latter, as non-financial recessions are not preceded by an expansion of the financial sector's balance sheet or a credit-boom. Even though the model is stylized, it predicts and replicates the occurrence of the Great Recession, when confronted with a historical series of structural shocks. The chapter shows additionally how to introduce the core mechanism and occasional financial crises into a standard New-Keynesian dynamic general equilibrium model. Within this extended framework, a U-shaped behavior of the nominal interest rate is particularly likely to lead to financial instability - a pattern which preceded recent financial crises in the U.S. and Japan.

The chapter is part of an evolving literature which aims to integrate financial frictions, (endogenous) risk, and occasional financial crises into standard macroeconomic models. The chapter particularly focuses on three aspects, which I consider to be of first-order importance in this regard. First, the modeling of the financial sector's balance sheet and the financial sector's lending behavior are in accordance with current institutional realities and empirical evidence. In particular, I show how to introduce long-term defaultable debt into a general equilibrium model in a tractable way which gives a realistic representation of the financial sector's balance sheet. Second, financial crises arise endogenously and the likelihood of a financial crisis varies over the business cycle. Financial crises are unlikely to break out at any point in time, but rather if certain preconditions are met. Third, in order to capture the nonlinear dynamics characteristic to episodes of financial distress, a nonlinear global solution of the model is obtained. Several avenues for future research come to mind. First, it would be useful to develop macroeconomic models which consider an even more detailed balance sheet of the financial sector (introducing mortgages and different types of contracts like fixed and variable rate loans). Second, given standard macroeconomic models which include financial crises, are there policy interventions which can improve welfare (macro-prudential policies)? And third, new approaches and applications to solving models nonlinearly are needed such that nonlinear global solutions can become part of the standard toolkit of central banks.

Chapter II

The Time Varying Transmission of Monetary Policy Surprises

1 Introduction

The financial system plays a key role in the transmission of monetary policy. The impact of monetary policy on the economy can therefore depend on the state of financial markets and may change with business and financial cycles. For example, during a financial boom, optimistic investors can respond differently to monetary policy changes than during financial recessions when pessimism prevails. The response of investors is reflected in *financial* variables, such as asset prices, interest rates, and credit, which in turn affect *economic* variables, such as output and inflation. Given these considerations, this chapter models the economy as a time varying vector autoregression (VAR), which includes economic and financial variables and allows these variables to freely interact with each other. Within this environment, the chapter shows how to identify the time varying response of such variables to a monetary policy shock.

Monetary Policy Identification and Time Variation. If the interest lies in the response of financial variables to a monetary policy shock, two identification issues arise. First, financial markets may anticipate central banks' decisions before they are implemented and financial variables may incorporate such expectations at the time when they are formed and not necessarily when monetary policy changes actually occur. A monetary policy shock should therefore also come as a surprise to financial markets in order to obtain the response of financial variables. However, monetary policy shocks under popular identification approaches are not necessarily "surprise shocks". Identifications based on standard timing restrictions (Christiano, Eichenbaum and Evans, 2005, among others), sign restrictions (Uhlig, 2005), and a central bank's narrative records and internal forecasts (Romer and Romer, 2004) suffer from this problem. Second, more specific to an identification based on imposing timing restrictions, it is generally assumed that a monetary authority can either react contemporaneously to a financial variable or a financial variable can respond to a change in monetary policy within the same period - but not both. However, with respect to most financial variables, both directions are possible.

In order to address these identification problems, I follow Kuttner (2001) among others, and identify monetary policy shocks by the surprise component in policy announcements which are obtained from price changes in Federal Funds futures around such announcements. These monetary policy surprises enter the model as an exogenous variable and the interest lies in the response of the endogenous variables to these surprises. Under this alternative identification approach, all endogenous variables can react contemporaneously to monetary policy shocks, which also come as surprises to financial markets. The above shortcomings of the mentioned identification approaches therefore do not apply. Moreover, the impulse responses to the monetary policy surprises can vary over time, since the model allows for time variation in the coefficients to the lagged endogenous variables and in the coefficients to the exogenous variable (the monetary policy surprises). This holds both for the contemporaneous response, as well as for the subsequent response when the surprise propagates through the system via the lagged endogenous variables.

Relation to External Instrument Approach. The model is strongly related to a recent identification approach based on external instruments (Stock and Watson, 2012; Mertens and Ravn, 2013). Gertler and Karadi (2015) apply this approach and use monetary policy surprises as external instruments with respect to a constant parameter VAR. In an application of the model discussed below, I show that the "external instrument approach" leads to equivalent impulse responses with respect to a constant parameter VAR as the one in this chapter. Moreover, the "exogenous variable approach" in this chapter gives wider confidence bands regarding these impulse responses, since the series of monetary policy surprises is directly included into the VAR and it is therefore taken into account that the surprises are partly explaining the data for the computation of confidence bands.

Further, within the context of a time varying parameter VAR, it would be more involved to apply the "external instrument approach". The reason is that not only the estimation of the VAR itself has to allow for time variation in the coefficients, but also the necessary external steps related to the instrument. In contrast, the framework in this chapter does not require such external steps, since the monetary policy surprises are directly included in the VAR. It is only necessary that the coefficient vector with respect to the exogenous variable can vary over time, which largely simplifies the analysis.

These results may not just be specific to the field of monetary policy identification, but depending on the application can also hold for other identifications based on external instruments. The model may therefore have applications outside the specific context of this chapter, both with respect to constant and time varying parameter VARs.

Time Varying Response of Stock Prices. The framework is used to obtain evidence on the time varying response of stock prices to the monetary policy surprises. This response is potentially informative about the effectiveness of so-called "leaning against the wind policies" which aim to disinflate asset bubbles using monetary policy. The application of such policies is generally considered during boom and perceived bubble periods. The model is rigged to evaluate the impact of monetary policy on the stock market during these periods and may therefore indicate the effectiveness of such policies - while keeping in mind that drawing any definite policy recommendations from the analysis in this chapter would be subject to the Lucas critique.

The main results are as follows. Stock prices always persistently decrease after a monetary tightening and more strongly than fundamentals imply - with an increase in risk-premia explaining the difference. However, stock prices respond less during a boom and a perceived bubble period. The time varying response of stock prices suggests that the application of so-called "leaning against the wind policies" may be questionable. If stock prices are responding less during periods when such policies would be applied, then they may be ineffective. Thus, the findings in this chapter indicate that monetary policy may not be suitable to disinflate asset bubbles and other policy tools could be considered to "lean against the wind".

What explains the time varying impact of monetary policy on stock markets? There are at least two possible explanations. First, as argued by Galí (2014) and Galí and Gambetti (2015), if a rational bubble is present in stock markets, then stock prices are less responsive if they comprise such a bubble which does not respond initially to a change in monetary policy. Hence, the time varying response of stock prices may indicate the presence of a rational bubble. Second, the time varying response of stock prices could also be explained by a time varying response of risk-premia and fundamentals, and the model shows how to disentangle the two, under the assumption that a rational bubble is not present. The results show that the time varying response of stock prices is largely due to the time varying response of risk-premia, which may be less responsive during booms and perceived bubble periods because investors are (over-)optimistic during such periods.

The analysis in this chapter relates to the one by Galí and Gambetti (2015), who also test for the time varying response of stock prices to monetary policy shocks. However, they identify monetary policy shocks by imposing timing restrictions with the two concerns which are mentioned above. They find protracted periods during which stock prices *increase* after a monetary tightening, while prices based on fundamentals decrease. These results are difficult to reconcile with the response of risk-premia which would have to decrease after a monetary tightening in order to explain the findings. However, theoretical and empirical papers generally argue that risk-premia increase after a monetary tightening (Drechsler, Savov and Schnabl, 2015; Bernanke and Kuttner, 2005). Galí and Gambetti (2015) conclude that their results cannot be explained by the response of risk-premia and instead indicate the presence of a rational bubble. The latter is a possible explanation for their results, since Galí (2014) points out that contractionary monetary policy which raises the real interest rate in the short run increases the growth rate of a rational bubble and may therefore *increase* its size. Hence, if a rational bubble is present in stock markets, stock prices can increase after a monetary tightening.

However, the findings in this chapter show that the results by Galí and Gambetti (2015) depend on their identification approach. In contrast to their findings, this chapter shows that stock prices always decrease after a monetary tightening, more strongly than prices based on fundamentals imply, and the time varying response of stock prices could also be explained by a time varying response of risk-premia and fundamentals. However, while the results differ, the suggestions with respect to policy do not. Galí (2014) and Galí and Gambetti (2015) argue against the use of "leaning against the wind policies" since they may have the opposite of the intended effect on asset bubbles according to their analysis.

The chapter is organized as follows. The next section relates the econometric model and its application to other contributions in the literature - apart from the ones already mentioned in the introduction. Section 3 outlines the econometric framework in a generic way and section 4 considers its specific use in the context of monetary policy identification. Section 5 applies the model and obtains evidence on the time varying impact of monetary policy on stock markets. Section 6 concludes.

2 Related Literature

The econometric framework in this chapter builds on the literature of time varying vector autoregressive models. This literature evolved according to the sources of time variation. Cogley and Sargent (2001) allowed the coefficients in a VAR to drift over time and later extended their framework by allowing for heteroscedastic innovations (Cogley and Sargent, 2005). Building upon their work, Primiceri (2005) also considered a time varying variance covariance matrix of the innovations, but allowed both for time variation in the simultaneous relations among the variables of the model and for heteroscedasticity of the innovations. This chapter uses time varying VARs as in Cogley and Sargent (2001) and Primiceri (2005), but additionally includes an exogenous variable and the coefficients with respect to this variable are allowed to vary over time.

The exogenous variable is a series of monetary policy surprises with the relation to the external instrument approach mentioned in the introduction. The novelty of this chapter is to identify monetary policy shocks using surprises obtained from future contracts in a time varying vector autoregressive model.

The application of the model is related to an empirical literature on the impact of monetary policy on stock markets. Apart from the work by Galí and Gambetti (2015), this literature has looked at the response of stock returns around policy meetings. Bernanke and Kuttner (2005) obtain daily surprises from future contracts based on the approach developed by Kuttner (2001). They find that a 25 basis point cut is associated with a 1% increase in stock returns. Gürkaynak, Sack and Swanson (2005) consider intraday data in order to extract surprises within a narrower window and find similar quantitative effects as Bernanke and Kuttner (2005). Rigobon and Sack (2004) find partly larger effects using an identification through heteroscedasticity.

More recently, Jansen and Zervou (2015) obtained evidence on the time varying response of stock returns around policy meetings. They find that stock returns are less responsive during perceived bubble periods which Jansen and Zervou (2015) explain with the presence of a rational bubble as suggested by Galí (2014). In line with their results, I show that stock prices exhibit a similar time varying response, but this response may also be explained by the time varying response of the underlying fundamentals and risk-premia, and not necessarily with the presence of a rational bubble, and the framework by Jansen and Zervou (2015) cannot speak to these alternative explanations. Moreover, in contrast to all of the mentioned contributions apart from Galí and Gambetti (2015), this chapter considers a VAR and traces out the response of the variables included in the VAR to monetary policy shocks at longer horizons - allowing one to look at the dynamic response of stock prices, their underlying fundamentals, and risk-premia.

3 Econometric Model

This section presents the econometric model in a generic way and the following sections outline its specific use in the context of monetary policy identification. Here, all sources of time variation are considered. The models with respect to the application below illustrate how the results change when some of these sources are held constant. I consider a time varying vector autoregressive model which follows the specification in Primiceri (2005), but additionally includes an exogenous variable. The description of the model is kept brief and further motivation for the modeling choices can be found in Primiceri (2005), whose notation I largely adopt to ease comparison. Let y_t be an $n \times 1$ vector of endogenous variables and consider the model

$$y_t = B_{0,t} + \sum_{j=1}^{k} B_{j,t} y_{t-j} + B_{k+1,t} z_t + u_t \qquad t = 1, ..., T \tag{19}$$

where $B_{0,t}$ is a $n \times 1$ vector of time varying intercepts and $B_{j,t}$ for $j \in \{1, ..., k\}$ are $n \times n$ time varying coefficient matrices with respect to the lagged endogenous variables. The model includes an exogenous variable z_t with $n \times 1$ vector of time varying coefficients $B_{k+1,t}$. The innovations are given by the $n \times 1$ vector u_t and the model allows for stochastic volatility such that the variance covariance matrix Ω_t of these innovations is time varying. Stochastic volatility can be accounted for in many ways. Here, I follow the parsimonious specification of Primiceri (2005) and consider a triangular reduction of Ω_t, given by

$$A_t \Omega_t A_t' = \Sigma_t \Sigma_t'$$

where A_t is a lower triangular matrix and Σ_t is a diagonal matrix

$$A_t = \begin{bmatrix} 1 & 0 & .. & 0 \\ a_{21,t} & 1 & .. & .. \\ .. & .. & 1 & 0 \\ a_{n1,t} & .. & a_{nn-1,t} & 1 \end{bmatrix}, \quad \Sigma_t = \begin{bmatrix} \sigma_{1,t} & 0 & .. & 0 \\ 0 & \sigma_{2,t} & .. & .. \\ .. & .. & .. & 0 \\ 0 & .. & 0 & \sigma_{n,t} \end{bmatrix}$$

such that the model's innovations can be expressed as $u_t = A_t^{-1}\Sigma_t\epsilon_t$ where ϵ_t is a $n \times 1$ vector of uncorrelated, unobservable shocks with unit variance. Hence, the model considers four sources of time variation: (i) the coefficients with respect to lagged endogenous variables, (ii) the contemporaneous relation between the endogenous variables and the exogenous variable, (iii) the contemporaneous relation between the endogenous variables and the unobservable shocks ϵ_t via A_t, and (iv) the volatility of these shocks via Σ_t.

Next, define B_t to be a vector which stacks all coefficients on the right-hand side of (19) - coefficients to the constant terms, to the lags of the endogenous variables, and to the exogenous variable. Further, denote α_t to be a row vector which stacks all elements of A_t below the diagonal and $\log\sigma_t$ to be a vector of the logarithm of the diagonal elements of Σ_t. The evolution of these three vectors is assumed to be given by

$$\begin{aligned} B_t &= B_{t-1} + v_t \\ \alpha_t &= \alpha_{t-1} + \zeta_t \\ \log\sigma_t &= \log\sigma_{t-1} + \eta_t \end{aligned}$$

such that B_t, α_t, and $\log\sigma_t$ follow driftless random walks. Moreover, the model's innovations are assumed to be jointly normally distributed and the variance covariance matrix to be block diagonal which takes the form

$$V = \text{Var}\left(\begin{bmatrix} \epsilon_t \\ v_t \\ \zeta_t \\ \eta_t \end{bmatrix}\right) = \begin{bmatrix} I_n & 0 & 0 & 0 \\ 0 & Q & 0 & 0 \\ 0 & 0 & S & 0 \\ 0 & 0 & 0 & W \end{bmatrix}$$

where Q, S, and W are positive definite matrices and termed 'hyperparameters'.[22] Denote by $\Pi^\tau = [\pi_1', ..., \pi_\tau']'$ the history of a vector of variables π_t for $t = 1, ..., \tau$ which consists of the time

[22] Again following Primiceri (2005), I assume that S is block diagonal which simplifies the estimation.

varying elements of a vector or a matrix Π_t. Bayesian methods and Gibbs sampling are used to evaluate the posterior distributions of the history of coefficients B^T and A^T, volatilities Σ^T, and the hyperparameters V. The estimation algorithm closely follows Primiceri (2005) and the steps of the sampler are summarized in Appendix C.1, taking into account the corrections in Del Negro and Primiceri (2015).

Weak Exogeneity. An important assumption of the model is that z_t is "weakly exogenous" (Engle, Hendry and Richard, 1983). Under weak exogeneity, analyzing the conditional model for y_t given its lags and z_t as in (19) is without loss of information for the evaluation of the posterior distributions of the parameters of interest collected by $\psi_t = (B_t, \alpha_t, \log\sigma_t, V)$.[23] Hence, nothing more can be learned about the posterior distributions of ψ_t from modeling y_t and z_t jointly. If z_t is weakly exogenous, it can be considered as determined outside of the model for y_t and understood as the statistical formalization of taking z_t as 'given'. Weak exogeneity requires that no natural or imposed cross-restrictions or dependencies between the prior and posterior distributions of the parameters of the conditional model of y_t (given z_t and lags of y_t) and the ones of a marginal model for z_t (given lags of y_t) exist and the two can vary freely. With respect to the specific application of the model considered below, no such restrictions exist. Hence, the efficient evaluation of the posterior distributions of ψ_t can be achieved by the model described in (19) and the analysis abstracts from a model for z_t.

4 Monetary Policy Identification

The model is outlined in a generic way and largely follows the specification in Primiceri (2005) with the only difference that I additionally include an exogenous variable and allow the coefficients on this variable to vary over time. Next, I consider a more specific setting and explain the role of the model's sources of time variation within this context.

[23]The original formulation of weak exogeneity by Engle, Hendry and Richard (1983) did not consider a Bayesian approach. Concepts of exogeneity from a Bayesian point of view, for which the interest lies in the posterior distribution of the parameters of interest, are discussed in Florens, Mouchart and Rolin (1990).

Assume that y_t is a vector of both economic and financial variables. The interest lies in the time varying response of these variables to a monetary policy shock. As mentioned in the introduction, popular identification approaches based on timing restrictions (Christiano, Eichenbaum and Evans, 2005), sign restrictions (Uhlig, 2005), or central banks' narrative sources and internal forecasts (Romer and Romer, 2004) are undesirable in such a context, because monetary policy shocks identified with such methods do not necessarily come as surprises to financial markets. An approach based on timing restrictions is additionally too restrictive with respect to contemporaneous relations.

4.1 Monetary Policy Surprises

In order to address these identification problems, I rely on monetary policy shocks which are identified from high frequency futures price data around policy announcements which capture the surprise component in such announcements. In particular, I consider surprises extracted from Fed Funds futures which are settled at the end of the month t during which a policy announcement is made. Let f_t^k be the settlement price for the current month's Fed Funds future following an FOMC meeting k which takes place in month t. Denote by $f_{t,-1}^k$ the settlement price prior to the FOMC meeting k in month t. Then, a surprise $\mathbb{S}_t^k$ around FOMC meeting k is given by

$$\mathbb{S}_t^k = f_t^k - f_{t,-1}^k$$

which is measured in a 30-minute window around a policy announcement.[24,25] This gives a sufficiently tight window such that a potential bias due to other information released around the policy announcement is minimized (and to which financial markets and the monetary authority could react).[26] The series of surprises $\mathbb{S}_t^k$ are on a meeting-by-meeting basis and are converted into a time series of surprises $\mathbb{S}_t$ which has the same frequency as the variables

[24]The surprise series are based on calculations in Gertler and Karadi (2015) and Gürkaynak, Sack and Swanson (2005). I thank Peter Karadi and Mark Gertler for sharing their data in this regard.

[25]When considering Federal Funds future contracts with respect to the current month, one additionally has to adjust the surprise series for the remaining days within a month, since 30-day Federal Funds futures are bets on the average Federal Funds rate within a month. In this regard, the surprise series are adjusted as suggested by Kuttner (2001), multiplying $\mathbb{S}_t^k$ by $\frac{T}{T-m}$ where T is the total number of days in month t and m the number of days which have elapsed until meeting k.

[26]The tight window also speaks against the concern of measurement error in the monetary policy surprises.

which enter the VAR. If multiple FOMC meetings occur within a period t, then the surprises with respect to these meetings are summed up (as in Romer and Romer, 2004).[27]

4.2 Impulse Response Analysis

The resulting series of surprises $\mathbb{S}_t$ enter the model as the exogenous variable z_t. An impulse response of the endogenous variables for horizon $t+h$ to a monetary policy surprise of size x at time t is then defined as

$$E\left(y_{t+h}|\overline{B}_t, z_t = x\right) - E\left(y_{t+h}|\overline{B}_t, z_t = 0\right) \quad \text{for } \; h \geq 0 \tag{20}$$

given the estimated model outlined above and the posterior mean of the model's coefficients collected in $\overline{B}_t$ at time t. The vector $\overline{B}_t$ also includes the posterior mean $\overline{B}_{k+1,t}$ which gives the contemporaneous response of y_t to a variation in z_t. When estimating the model, further restrictions can be imposed upon $\overline{B}_{k+1,t}$, such as zero restrictions with respect to slow-moving macro variables.

In what follows, I use the terms monetary policy shock and monetary policy surprise interchangeably and consider impulse responses to monetary policy shocks as defined in (20).[28] Given this definition, monetary policy shocks come as surprises to the economy and the endogenous variables can respond contemporaneously to monetary policy shocks. Moreover, this contemporaneous response is allowed to vary over time as well as the propagation of the shock through the system via the lagged endogenous variables. The model is therefore equipped to identify the time varying impulse responses of a system with both economic and financial variables to monetary policy shocks.

[27]The series of surprises used for the main analysis in this chapter excludes inter-meeting surprises and only considers surprises with respect to scheduled FOMC meetings. Since I estimate a monthly VAR and there are never two scheduled FOMC meetings within a particular month, this series does not require to aggregate surprises within a particular month.

[28]Bagliano and Favero (1999) and Favero and Giavazzi (2012) obtain impulse responses in similar ways with respect to constant parameter VARs.

4.3 Strong Exogeneity

The conditional model in (19) together with the impulse response analysis as stated in (20) may be missing a potential feedback loop. This is the case if the marginal model of z_t depends on lagged values of y_t, i.e. y_t is Granger-causing z_t. For example, z_t could depend on y_{t-1}

$$z_t = \beta y_{t-1} + \xi_t \qquad t = 1, ..., T \tag{21}$$

where β is a constant $1 \times n$ vector and ξ_t is the innovation to this equation. In this case, an impulse response of y_t to a change in z_t affects next period's z_{t+1} via equation (21), which in turn has an impact on y_{t+1} via (19) and so on. However, this feedback loop is not active if y_t is not Granger-causing z_t, which is testable for a specific application of the model. Engle, Hendry and Richard (1983) term z_t "strongly exogenous" if two conditions are satisfied. First, z_t is weakly exogenous. Second, y_t does not Granger-cause z_t. I confirm that the monetary policy surprises in the application described next are not only weakly, but also strongly exogenous, such that the lagged values of the endogenous variables included in the VAR do not predict the monetary policy surprises - an intuitive result, since the opposite would indicate that the Federal Funds futures market is somehow inefficient.

5 The Time Varying Response of Stock Prices

The described framework and impulse response analysis are used to obtain evidence on the time varying response of stock prices to the monetary policy surprises. As mentioned in the introduction, this response is potentially informative about the effectiveness of so-called "leaning against the wind policies". The impact of monetary policy on the stock market may change over time and the framework can be used in order to understand if stock prices are more or less responsive during boom and perceived bubble periods when such policies would be applied. The analysis is strongly related to the one in Galí and Gambetti (2015) who also test for the time varying response of stock prices to monetary policy shocks which are identified via timing restrictions. Their paper is motivated by the theoretical predictions in Galí (2014) regarding the relation between monetary policy and a rational bubble. The next section briefly summarizes the main ideas of these two papers and the reader wishing to understand the results of this chapter can skip this section.

5.1 Monetary Policy and Rational Bubbles

Consider a partial equilibrium example as in Galí (2014). The economy is populated by risk-neutral investors and the real interest rate is exogenous and time-varying. Further, assume there exists an infinitely-lived asset which is priced according to the following equation

$$P_t R_t = \mathbb{E}_t(D_{t+1} + P_{t+1}) \tag{22}$$

where D_{t+1} is the dividend that this asset pays in period $t+1$. If a transversality condition is not imposed, then the price P_t of this asset can be decomposed into a fundamental part and a bubble part b_t

$$P_t \quad = \quad P_t^F + b_t \tag{23}$$

with $b_t > 0$. The fundamental part P_t^F is defined as the sum of the expected present discounted value of all future dividends

$$P_t^F \equiv \mathbb{E}_t \left[\sum_{s=1}^{\infty} \left(\prod_{j=0}^{s-1} R_{t+j}^{-1} \right) D_{t+s} \right] \tag{24}$$

If a rational bubble exists and the fundamental price P_t^F is smaller than the price of the asset P_t, then the bubble has to satisfy the equilibrium condition that its expected growth rate is equal to the real interest rate in the economy

$$\mathbb{E}_t \left[\frac{b_{t+1}}{b_t} \right] = R_t \tag{25}$$

Starting from this equation, Galí (2014) observes that an increase in the real interest rate R_t leads to an increase in the expected growth rate of the bubble. Moreover, given the inherent indeterminacy of the size of the bubble b_t under the rational bubble theory, it would be arbitrary to assume a contemporaneous impact of monetary policy on the bubble. A monetary policy tightening therefore increases the bubble over time, as the real interest rate rises in the short run which increases the bubble's growth rate. This result is in contrast to the conventional wisdom about the relation between monetary policy and bubbles which goes the other way around - a monetary tightening is able to disinflate bubbles.

Given these theoretical predictions, the response of stock prices to a monetary policy shock should depend on whether stock prices contain a bubble component as in equation (23) or not. After a monetary tightening, the fundamental part (24) decreases since dividends decline and the real interest rate increases. However, the larger the bubble component in (23), the more the initial decrease in stock prices may be *dampened* since the contemporaneous impact of monetary policy on the bubble is indeterminate and the bubble is therefore unlikely to react initially. Further, over time stock prices should increase, due the recovery of the fundamental component and due to the increase of the bubble as argued by Galí (2014). In fact, stock prices can even increase above and beyond the response of prices based on discounted dividends and constant risk-premia, if the bubble is sufficiently large and risk-premia are not increasing enough to off-set these effects by lowering prices.

Motivated by these theoretical predictions, Galí and Gambetti (2015) ask whether the data supports the existence of rational bubbles in stock markets. Given that such a bubble is present in stock markets, the response of stock prices to a monetary policy shock should differ between "normal times" and "bubble periods". Galí and Gambetti (2015) estimate a time varying parameter VAR following the specification in Primiceri (2005). They include quarterly US data for GDP, the GDP deflator, a commodity price index, the Federal Funds rate, a stock price index (S&P 500) and the associated dividends into their model. In order to identify monetary policy shocks, Galí and Gambetti (2015) impose the timing restrictions that monetary policy responds to output, inflation, the commodity price index, and dividends contemporaneously, but these variables respond with a lag to a change in the Federal Funds rate. In contrast, monetary policy does not respond to stock prices contemporaneously, but stock prices are allowed to respond within the same period to a change in monetary policy. Galí and Gambetti (2015) find protracted periods during which stock prices *increase* following a monetary tightening and *above* prices based on discounted dividends and constant risk-premia. These results are at odds with bubbless models which predict that stock prices should decrease after a monetary tightening and this decrease should be stronger than the response of prices based on fundamentals if risk-premia increase as well. Hence, their findings support the existence of rational bubbles in stock markets.

However, the results by Galí and Gambetti (2015) may depend on the monetary policy identification approach and the two concerns with respect to an identification based on timing restrictions which were mentioned above apply. First, monetary policy shocks obtained via timing restrictions do not necessarily come as surprises to financial markets and the obtained impulse response of stock prices may differ from the one to a "surprise shock". And second, a monetary authority may be reacting contemporaneously to stock prices because they contain information about future economic activity or since they influence the real economy (Rigobon and Sack, 2003).[29] The model outlined above is able to test whether these identification problems indeed play a role in this context.

5.2 Data

I estimate a monthly model for the U.S. economy. Define the vector of endogenous variables

$$y_t \equiv [i_t, \Delta q_t, \Delta d_t, \Delta p_t, \Delta \widetilde{y}_t]'$$

where i_t denotes the Federal Funds rate, q_t the (log) real stock price index (S&P 500), d_t the associated (log) real dividends, p_t the (log) consumer price index (CPI), and $\widetilde{y}_t$ (log) real

[29] Galí and Gambetti (2015) do find that their results change if they allow monetary policy to respond contemporaneously to stock prices when restricting the parameter on this response. However, they argue that the calibration of this response parameter has to be too high compared to other estimates of this parameter in the literature in order to overturn their results.

industrial production (IP).[30,31] Regarding the exogenous variable z_t, surprises in the current month's future rate around FOMC meetings are used. The series of surprises is based on 30-day Federal Funds rate futures which started trading in 1988M11 and is available until 2012M6 - restricting the estimation of the model to this sample period.[32]

5.2.1 The Fed's Information Advantage

A potential concern with respect to the series of monetary policy surprises is that the Fed may have an information advantage over the private sector and releases this information when changing interest rates. The impulse response of stock prices may therefore be affected by the release of this information.

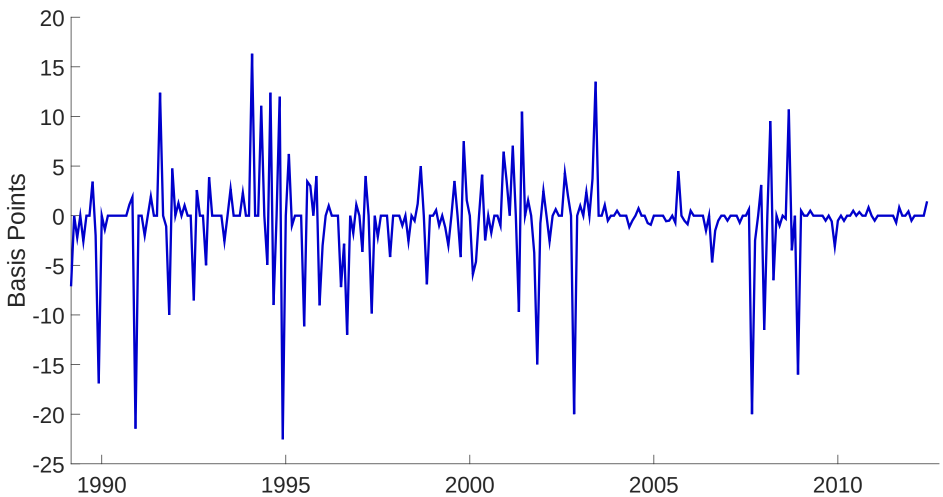

Figure 15: ***Monetary Policy Surprises.*** *Surprises from the current month's 30-day Federal Funds future around scheduled FOMC meetings. The surprises are measured in a 30-minute window around policy announcements and adjusted for the remaining days within a month.*

[30]See Appendix C.5 for the time series in log-levels and in first-differences.

[31]The time series of stock prices is based on the end of the month price of the S&P 500. The time series of the associated dividends is the one provided on Robert Shiller's webpage for monthly U.S. data.

[32]The sample is shorter than the one considered by Galí and Gambetti (2015) who estimate their model for 1960Q1-2011Q4. However, Galí and Gambetti (2015) find that the probability of a positive response of stock prices and the probability of a positive difference between stock prices and prices based on discounted dividends increases strongly after the mid-1980s and stays high afterward. Since the external instrument approach by Gertler and Karadi (2015) does not require the instrument series to be continuously available, I apply their method to the sample 1960M1-2011M12 with respect to a constant parameter VAR and the results are shown in Appendix C.4, which are consistent with the findings in the sections below. Section 5.4 and Appendix C.4 explain the differences between the "external instrument approach" and the method in this chapter.

For example, if the Fed believes that the economic outlook is worse than the private sector envisions, then a monetary easing expresses this belief and stock prices may be increasing less since they partly respond to the release of the Fed's private information. In order to address this concern, I follow Faust, Swanson and Wright (2004) and Barakchian and Crowe (2013) and exclude monetary surprises around *unscheduled* FOMC meetings. Such meetings generally occur in environments of high economic uncertainty, when the dispersion of forecasts is large, and the Fed may be particularly likely to release private information by changing interest rates with respect to such meetings. In contrast, there is empirical evidence that the information advantage of the Fed around *scheduled* FOMC meetings is small (Barakchian and Crowe, 2013, Gertler and Karadi, 2015). I confirm this evidence in the sensitivity analysis in section 5.7 by projecting the monetary policy surprises around scheduled FOMC meetings on an empirical proxy for the Fed's private information and show that the empirical proxy can only explain a small part of the surprises' variation. As an additional robustness check, the residuals from this regression are used to re-estimate the models below and the results remain largely unchanged. The series of monetary policy surprises which is used in the following estimations is shown in Figure (15).

5.2.2 Weak and Strong Exogeneity

The considered series of monetary policy surprises z_t is weakly exogenous, since no natural or imposed cross restrictions or dependencies between the prior and posterior distributions of the parameters ψ_t and the ones with respect to the (hyper)parameters of a potential marginal model for z_t exist and the two are "variation free". If y_t does not Granger-cause z_t, then z_t is not only weakly, but also strongly exogenous. I confirm that z_t is indeed strongly exogenous using a series of regressions with z_t as the dependent variable and lagged values of y_t as explanatory variables (one to five lags are considered and the coefficients are assumed to be constant over time). The results are reported in Appendix C.3 and the related F-tests show that the lagged values of y_t are never significant at the 10% confidence level - indicating that the Federal Funds futures market is not inefficient in this regard.

Given that z_t is weakly and strongly exogenous, the conditional model in (19) is used in the estimations and impulse responses are obtained via (20). Next, I consider a series of vector autoregressive models which differ in terms of the time variation of their parameters. First, a VAR with constant parameters is estimated to illustrate the impulse responses for the whole sample. I show that this specification relates to the approach by Gertler and Karadi (2015) who use monetary policy surprises from future contracts as external instruments. Second, I consider a VAR with time variation in the coefficients with respect to the endogenous variables and the exogenous variable, but with a constant variance covariance matrix of the innovations such that Ω is time invariant (resembling the model of Cogley and Sargent, 2001). And third, in addition the last specification, Ω is allowed to vary over time following the modeling approach by Primiceri (2005), since the time variation in the coefficients with respect to the second specification may be overstated if Ω is indeed time varying.

For all these specifications, I impose restrictions on the contemporaneous response of slow-moving macro variables to a monetary policy surprise. Following Christiano, Eichenbaum and Evans (2005) among others, it is assumed that the consumer price index and industrial production do not respond contemporaneously to a monetary policy shock. However, the fast-moving variables (Federal Funds rate, dividends, stock prices) are allowed to respond contemporaneously. In section 5.7, I check the sensitivity of the results with respect to these short-run restrictions.

5.3 Constant Parameter VAR

In order to gain some initial intuition, a VAR with constant parameters is estimated such that the coefficients collected in B and the variance-covariance matrix Ω are time invariant.[33] Figure (16) shows the impulse response functions (IRFs) to a contractionary monetary policy

[33] A lag length of $k = 4$ is chosen based on Akaike's information criterion. The following time varying VARs are estimated for the same lag length.

surprise for this baseline specification.[34] The Federal Funds rate and the real interest rate (indicated by the red dotted line in the same plot) both increase in the short run. The model shows 'standard' responses of macroeconomic variables since industrial production and the consumer price index both decrease. However, the response of CPI is not significantly different from zero at the 95% confidence level. Most importantly, the stock price index decreases persistently following a monetary tightening which is in contrast to the results by Galí and Gambetti (2015) for this sample period. The response is also stronger than the implied response of prices based on fundamentals which is indicated by the red dotted line in the same plot and obtained via the impulse responses of dividends, the real interest rate, and constant risk-premia (see Appendix C.2 for a derivation).

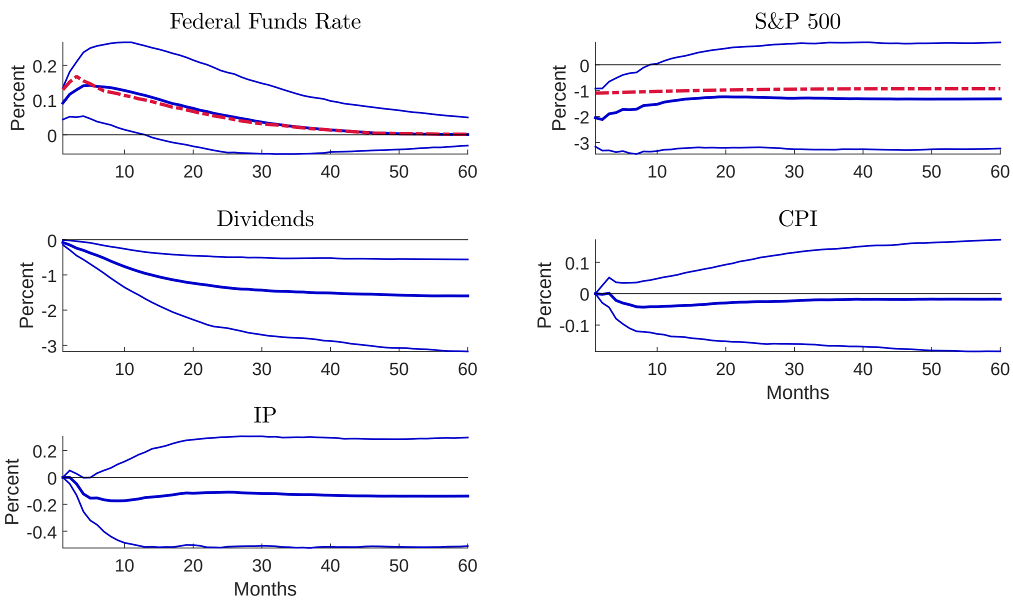

Figure 16: ***Impulse Response Functions.*** *IRFs to a contractionary monetary policy surprise, normalized to the standard deviation of the residual from the Federal Funds rate equation. Median responses and* 95% *confidence bands are shown. The red dotted line in the plot of the Federal Funds rate shows the real interest rate. The red dotted line in the plot of the S&P 500 shows the response of stock prices based on discounted dividends and constant risk-premia (see Appendix C.2 for a derivation).*

[34] Confidence bands are computed via a "wild bootstrap" as in Mertens and Ravn (2013) and Gertler and Karadi (2015). 10,000 bootstrap repetitions are used to obtain the impulse responses.

The difference in the response of stock prices versus the response of prices based on fundamentals can be accounted for by an increase in risk-premia following a monetary tightening. The results are therefore in line with the findings in Bernanke and Kuttner (2005) who show that stock returns decrease after a monetary tightening and that risk-premia account for a large part of this response. Moreover, the results also relate to empirical evidence on the volatility of the price-to-dividend ratio which can largely be explained by a variation of risk-premia (Cochrane, 2011). While it would be interesting to get a deeper understanding of the underlying factors which are responsible for an increase in risk-premia after a monetary tightening, it is out of scope of this chapter to provide such an analysis and the interested reader is referred to Cochrane (2011) who lists a range of existing theories which are causing variation in risk-premia and could also explain the response of risk-premia in this chapter.

5.4 Monetary Policy Surprises as External Instruments

The constant parameter VAR model relates to a recent identification approach by Gertler and Karadi (2015). As in this chapter, they consider a VAR with economic and financial variables and are interested in the response of these variables to a monetary policy shock. Gertler and Karadi (2015) also use surprises from future contracts in order to identify these responses. However, instead of including a series of monetary policy surprises directly into their VAR as an exogenous variable, they instead use the surprises as an external instrument following Stock and Watson (2012) and Mertens and Ravn (2013). First, Gertler and Karadi (2015) estimate an unrestricted VAR and obtain the residuals from this estimation. In a second step, they recover the relation between these residuals and the unobserved structural monetary policy shock by using a series of monetary policy surprises as an instrument for the structural monetary policy shock.

Appendix C.4 outlines their approach and shows the obtained impulse responses based on the data in this section. Their "external instrument" method is compared to the "exogenous variable approach" in this chapter. Since Gertler and Karadi (2015) do not impose short-run restrictions with respect to slow-moving macro variables, I re-estimate the constant parameter VAR without such restrictions and the obtained impulse responses are also shown in Appendix C.4. The impulse response functions using these two approaches are nearly equivalent, while the exogenous variable method gives wider confidence bands. The intuition for these findings is that the approach by Gertler and Karadi (2015) recovers the relation between the endogenous variables and the monetary surprises 'externally', while the method in this chapter recovers this relation 'internally' by including the surprise series directly into the VAR as an exogenous variable.[35] The confidence bands are wider using the exogenous variable approach, since the bootstrapping method additionally takes into account that the surprises are partly explaining y_t, which is not taken into account by the external instrument approach. While these two approaches lead to almost equivalent results with respect to a constant parameter VAR, applying the method by Gertler and Karadi (2015) within the context of a time varying parameter VAR would be more involved as the external steps would have to consider the time variation between the monetary policy surprises and the endogenous variables. In contrast, when including the surprises as an exogenous variable directly into the VAR, one only has to take into account that the coefficient vector $B_{k+1,t}$ with respect to the exogenous variable can vary over time, simplifying the analysis.[36]

5.5 Time Varying Parameter VAR - Ω

The evidence in Figure (16) shows that stock prices persistently decrease following a monetary policy tightening and this response is stronger than the response of prices based discounted dividends and constant risk-premia - with the difference representing an increase in risk-

[35]A difference between the two approaches is the following. Gertler and Karadi (2015) estimate their VAR first on a longer sample than their monetary surprise series is available, restrict the residuals from this estimation to the sample period for which the monetary policy surprise series is available, and then identify the contemporaneous relation between the monetary policy surprises and the endogenous variables for this smaller sample. This step-wise approach is not feasible within the econometric framework in this chapter since the monetary policy surprises are directly included into the VAR and the model is estimated for the sample for which all the time series are continuously available. In Appendix C.4, I make use of the step-wise approach and estimate the VAR for the long sample 1960M1-2011M12.

[36]De Wind (2014) considers the external instrument approach with respect to a time varying parameter VAR. But his method does not consider time variation in the external steps, such that the relation between the reduced form and the structural errors is time invariant. However, such constant contemporaneous relations are undesirable in a context where simultaneous relations are important as in this chapter.

premia. However, while these results hold for the whole sample period, there may still be subperiods during which the response to monetary policy shocks changes - in particular during the perceived bubble period in the 1990s. The time varying VARs which follow are equipped to detect such time varying responses. First, I consider a VAR with time varying parameters collected in B_t, but constant variance covariance matrix Ω. The model therefore resembles the one in Cogley and Sargent (2001), but additionally includes an exogenous variable.

5.5.1 Priors

Bayesian methods are used to evaluate the posterior distribution of B^T and the hyperparameters

$$V = Var\left(\begin{bmatrix} u_t \\ v_t \end{bmatrix}\right) = \begin{bmatrix} \Omega & 0 \\ 0 & Q \end{bmatrix}$$

The prior distributions are calibrated based on a training sample of around 12 years (1978M11-1990M12). Unfortunately, for a large part of this sample, the series of monetary policy surprises is not available since the futures market only started trading in 1988M11. I therefore set the surprises equal to zero with respect to periods for which no data is available. While this is certainly a limitation with respect to the calibration of the priors, the robustness checks in section 5.7 show that this constraint does not affect the findings of the chapter. Based on the OLS estimates of a constant parameter VAR for the training sample, mean and variance of B_0 and scale matrix and degrees of freedom for the inverse-Wishart prior of Ω and Q are set to

$$\begin{aligned} B_0 &\sim N\left(\widehat{B}_{OLS}, 4 \cdot V(\widehat{B}_{OLS})\right) \\ \Omega &\sim IW\left(I_n, n+1\right) \\ Q &\sim IW\left(\kappa_Q^2 \cdot \tau \cdot V(\widehat{B}_{OLS}), \tau\right) \end{aligned}$$

broadly following the reasoning in Cogley and Sargent (2001) and Primiceri (2005) to obtain priors which are not completely flat, but largely uninformative. Based on a training sample, $\widehat{B}_{OLS}$ collects the OLS point estimates, $V(\widehat{B}_{OLS})$ their variance, and $\tau = 142$ is the size of the training sample. An important parameter is κ_Q which pins down the prior belief about the amount of time variation in B_t. For the main analysis, I set $\kappa_Q = 0.02$. This calibration is largely consistent with the literature. Cogley and Sargent (2001) set $\kappa_Q = 0.01$ and Primiceri (2005) considers values $\kappa_Q = \{0.01, 0.05, 0.1\}$ and choosing $\kappa_Q = 0.01$ for the main analysis - arguing that this value gives the model enough flexibility to incorporate time variation in the coefficients, without trying to explain outliers with the time variation in B_t. The robustness checks in section 5.7 report the results for $\kappa_Q = 0.01$. The simulation of the model is based on 12,000 iterations of the Gibbs sampler and the first 2,000 are discarded for convergence.[37]

5.5.2 Results

Figures (17), (18), and (19) show the time varying impulse response functions for the sample 1991M1-2012M6.[38] Again, the responses of the Federal Funds rate, the real interest rate, the consumer price index, and industrial production are in line with the 'standard' responses of these variables to a monetary tightening. The recent zero-lower-bound episode is reflected in the response of the Federal Funds rate which is close to zero since late 2008. Most importantly, the stock market index always decreases after a monetary tightening, but only mildly during the 1990s perceived bubble period, strongly during the early 2000s recession, and moderately during the boom starting around 2005. In between these periods, changes in the impulse responses tend to be smoothed by the Bayesian methods. Further, figure (18) shows that stock prices always respond more negatively than fundamentals imply and again, an increase in risk-premia can account for this difference.[39] Moreover, the time varying response of stock prices is largely due to the time varying response of risk-premia, which show a very similar pattern over the sample. Thus, the impact of monetary policy on the stock market changes

[37] I check parameter convergence via trace plots and autocorrelation functions of the draws. The results show that the estimation algorithm produces posterior draws efficiently.

[38] Appendix C.9 plots IRFs for selected periods and additionally shows their 95% confidence bands.

[39] Again, the response of the fundamental is obtained via the response of dividends, the real interest rate, and constant risk-premia. See Appendix C.2 for a derivation.

over time, with weaker responses of stock prices and risk-premia during a boom or a perceived bubble period and stronger responses during a recession.

These empirical results are in fact in accordance with the theoretical predictions with respect to a rational bubble. If such a bubble is present in stock markets, stock prices are less responsive, since the contemporaneous response of the bubble component is indeterminate and the bubble is therefore unlikely to respond. However, in contrast to the findings by Galí and Gambetti (2015), stock prices always decrease after a monetary tightening and respond more strongly than fundamentals imply - even during periods when bubbles are perceived to have been present. So while the time varying response of stock prices could imply the existence of a rational bubble, it can also be explained by a time varying response of risk-premia, which respond less during the 1990s perceived bubble period and the mid-2000s boom period. The results suggest that "leaning against the wind policies" which advise the use of monetary policy in order to disinflate stock market bubbles are potentially ineffective, because stock prices respond by less exactly at the point when such policies would like them to respond.[40]

[40] Appendix C.10 shows the time varying IRFs in a 2D-format (percent response against the horizon of the IRF) for stock prices, CPI, and IP. In particular, the response of IP varies less over time in the short run compared to the response of stock prices. This suggests that a monetary tightening has a relatively homogeneous impact on IP in the short run across booms and recessions. Hence, large changes in the policy target rate which are needed to disinflate asset bubbles can have sizeable adverse effects on real economic activity in the short run which lead to deviations from macroeconomic targets.

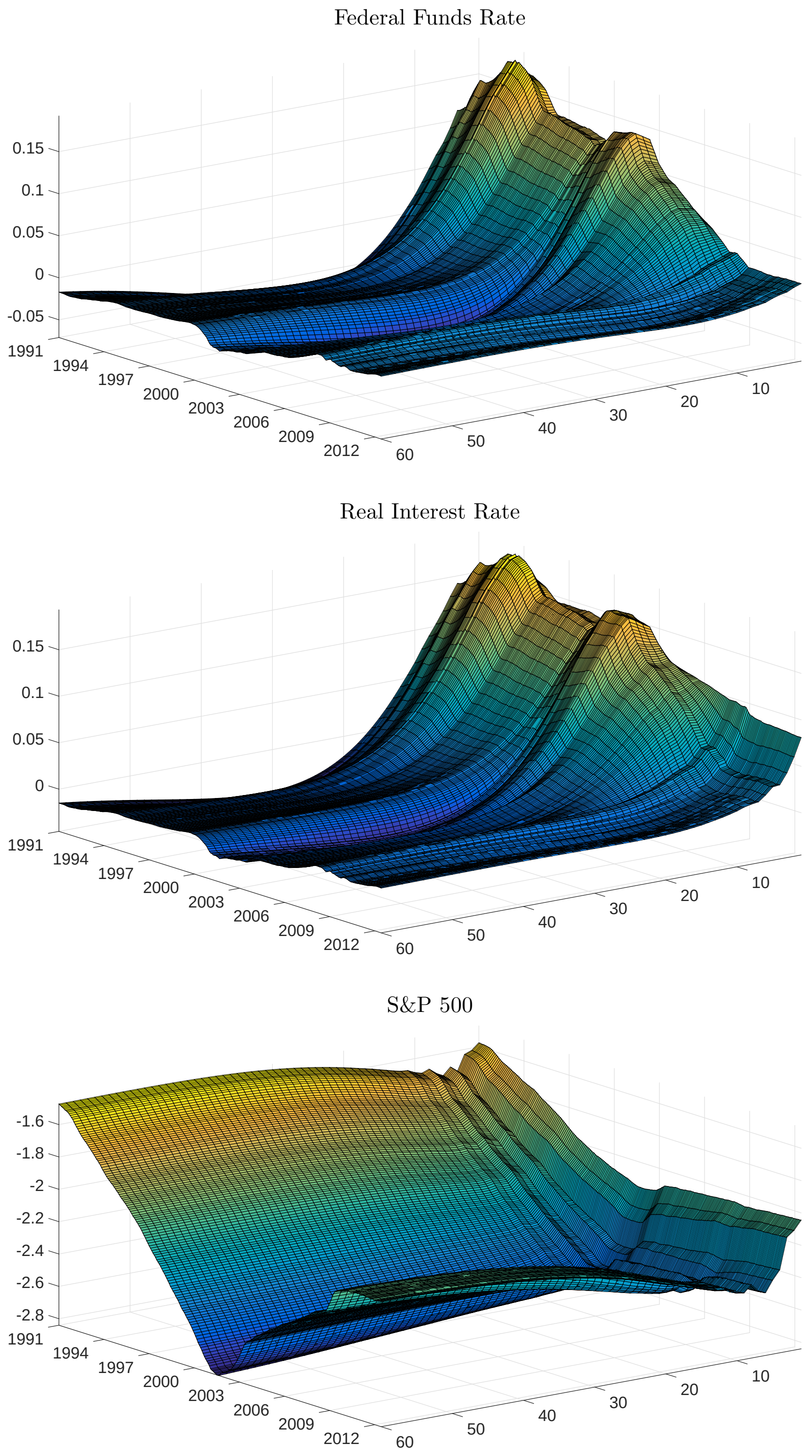

Figure 17: ***Time Varying Impulse Response Functions.*** *IRFs to a contractionary monetary policy surprise, normalized to the standard deviation of the residual from the Federal Funds rate equation. The responses are based on the posterior mean* $\overline{B}_t$ *for period* t *(see definition in equation (20)). Vertical axis: Percentage change. Front axis left: Years. Front axis right: Months (Horizon IRF).*

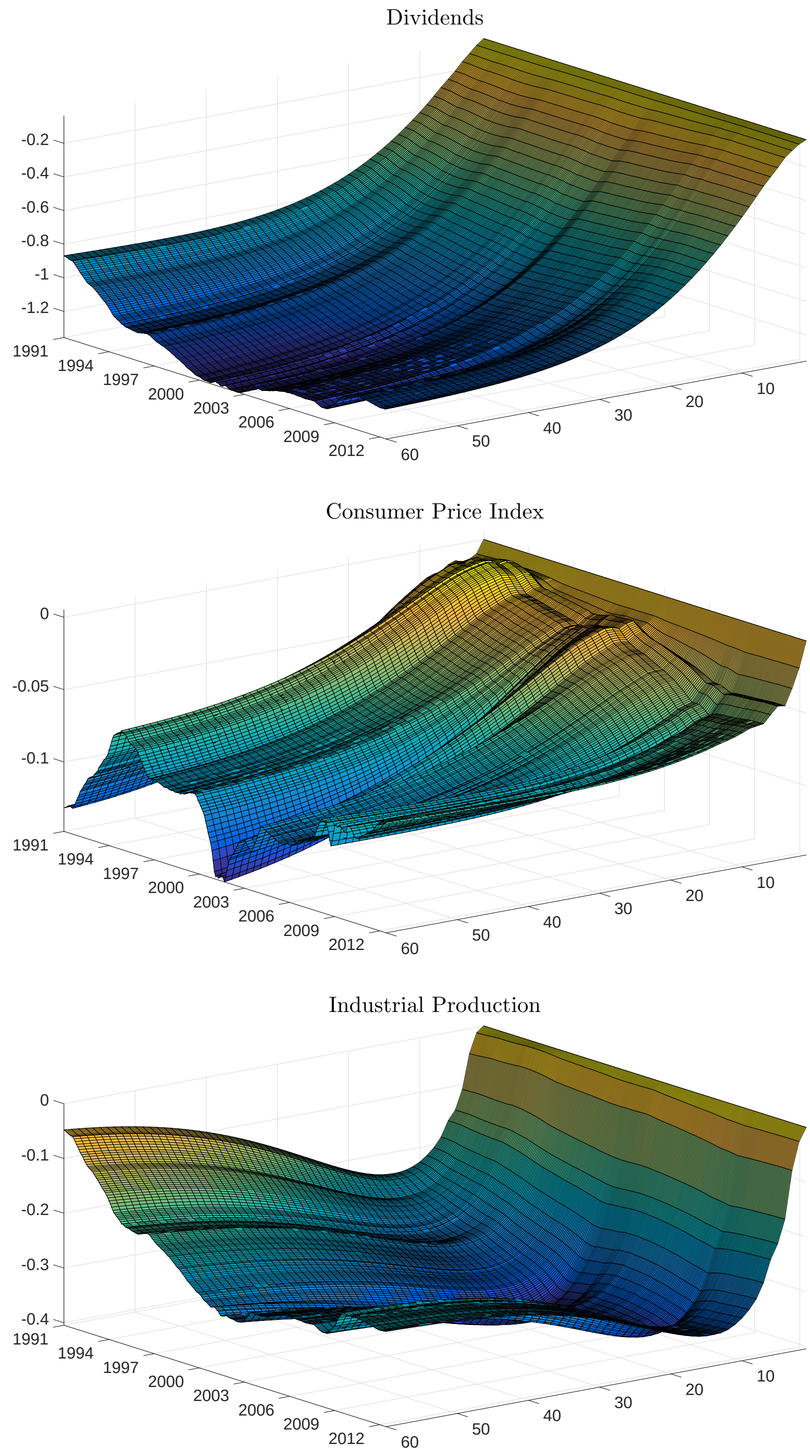

Figure 18: ***Time Varying Impulse Response Functions.*** *IRFs to a contractionary monetary policy surprise, normalized to the standard deviation of the residual from the Federal Funds rate equation. The responses are based on the posterior mean* $\overline{B}_t$ *for period* t *(see definition in equation (20)). Vertical axis: Percentage change. Front axis left: Years. Front axis right: Months (Horizon IRF).*

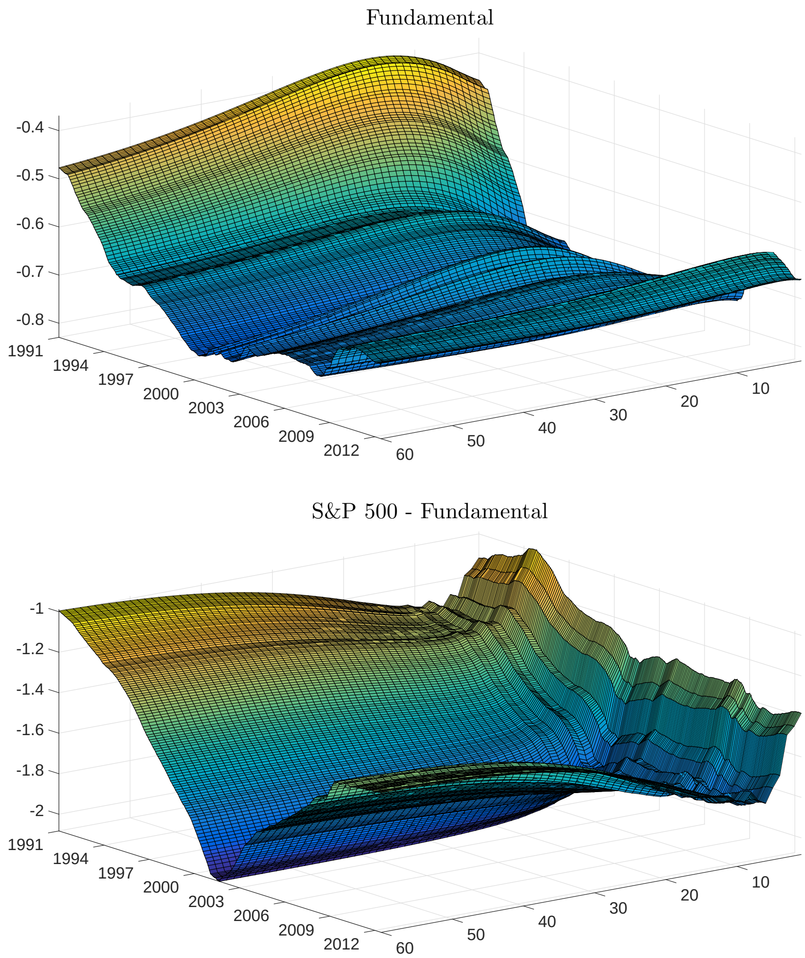

Figure 19: ***Time Varying Impulse Response Functions.*** *IRFs to a contractionary monetary policy surprise, normalized to the standard deviation of the residual from the Federal Funds rate equation. The responses are based on the posterior mean* $\overline{B}_t$ *for period* t *(see definition in equation (20)). Vertical axis: Percentage change. Front axis left: Years. Front axis right: Months (Horizon IRF).*

5.6 Time Varying Parameter VAR - Ω_t

As argued by Sims (2001) and Stock (2001) in response to the model by Cogley and Sargent (2001), allowing for time variation in the coefficients B_t, but not in the variance covariance matrix of the innovations Ω, may lead the model to over-represent the time variation in the coefficients B_t if the economy is indeed characterized by a time varying Ω_t. Hence, next I consider a time varying parameter VAR with time variation both in the coefficients collected in B_t as well as in the variance covariance matrix of the innovations Ω_t with the triangular reduction of Ω_t outlined in section 3.

5.6.1 Priors

The calibration of the prior distributions is again based on the training sample 1978M11-1990M12 and the one for B_0 and Q follows the reasoning in section 5.5.1. Similarly, the prior means for A_0 and $\log\sigma_0$ are set to the OLS estimates for the lower triangular matrix A and the logarithm of the standard errors of the constant parameter VAR based on the training sample. The calibration of the variance for A_0 and $\log\sigma_0$, as well as scale matrices and degrees of freedom of the inverse-Wishart priors for S_m and W follows the reasoning in Primiceri (2005) and are given by

$$\begin{aligned}
A_0 &\sim N\left(\widehat{A}_{OLS}, 4 \cdot V(\widehat{A}_{OLS})\right) \\
S_m &\sim IW\left(\kappa_s^2 \cdot (m+1) \cdot V(\widehat{A}_{m,OLS}), (m+1)\right) \\
\log\sigma_0 &\sim N\left(\log\widehat{\sigma}_{OLS}, I_n\right) \\
W &\sim IW\left(\kappa_W^2 \cdot (n+1) \cdot I_n, (n+1)\right)
\end{aligned}$$

where S is chosen to be block-diagonal, m gives the dimension of the block of S, and n is equal to the number of endogenous variables. Again following Primiceri (2005), I set $\kappa_S = 0.1$ and $\kappa_W = 0.01$ and check the sensitivity of the results to these choices in section 5.7. Given the calibration of the priors, the simulation of the model is again based on 12,000 iterations of the Gibbs sampler and the first 2,000 are discarded for convergence.

5.6.2 Results

The model's time variation in Ω_t is illustrated in figure (20) which shows the posterior mean, the 5th and the 95th percentiles of the standard deviation of the residuals with respect to each endogenous variable (the squared root of the diagonal elements of Ω_t). At the beginning of the sample, the standard deviation of the residual from the Federal Funds rate equation declines steadily, staying low for most of the sample, but sharply spiking up again at the beginning of the Great Recession, and most recently remaining close to zero when the Federal Funds rate is at the zero-lower bound. The standard deviation of the residuals from the dividends equation, the consumer price index equation, and the industrial production equation show similar paths. All remain relatively stable for most of the sample, but increase strongly during the Great Recession. The model also well picks up the volatile stock market periods from the end-1990s until around 2003 and the volatile period around the Great Recession.

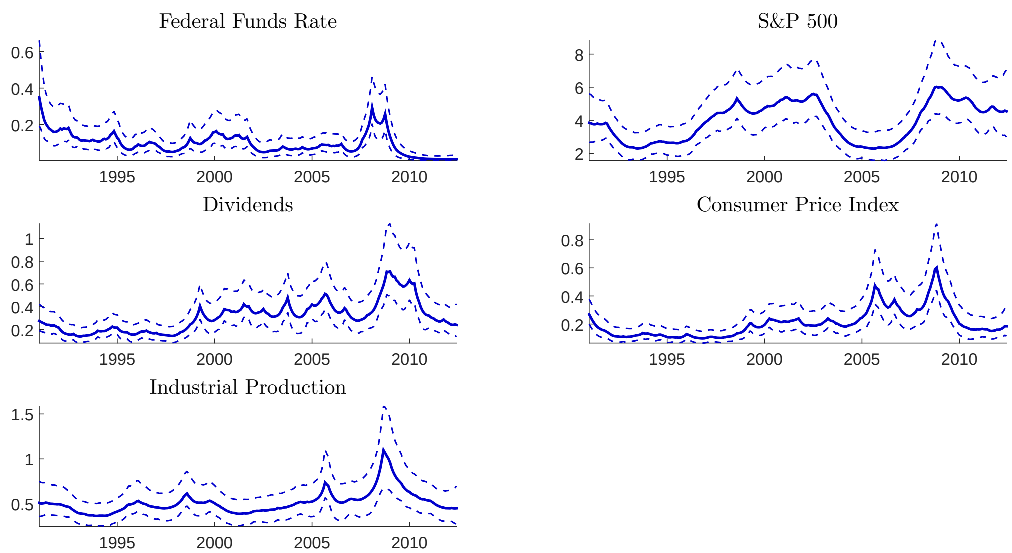

Figure 20: ***Time Varying*** Ω_t***.*** *Posterior mean, 5th and 95th percentiles of the standard deviation of the residuals with respect to each endogenous variable (the squared root of the diagonal elements of* Ω_t*).*

Again, I obtain evidence on the time varying impulse responses of the model's endogenous variables to a contractionary monetary policy shock according to the definition in equation (20), which are shown in figures (47), (48), and (49) for the period 1991M1-2012M6 in Appendix C.7.[41] The Federal Funds rate, the real interest rate, industrial production, and the S&P 500 respond similarly as in the model with a time invariant variance covariance matrix Ω. In contrast, the consumer price index increases mildly after a monetary tightening for the earlier part of the sample. However, I find that this increase is never significantly

[41] Appendix C.9 plots IRFs for selected periods and additionally shows their 95% confidence bands.

different from zero at the 95% confidence level.[42] The main conclusions with respect to the response of stock prices still hold. Stock prices always decrease following contractionary monetary policy and this response is stronger than the response of prices based on discounted dividends and constant risk-premia - with the difference reflecting an increase in risk-premia. Moreover, stock prices respond less during the 1990s perceived bubble period than during the early 2000s-recession, and again weaker afterwards. A difference to the Ω-model is that the response of risk-premia does not become weaker for the later part of the sample.[43]

5.7 Sensitivity Analysis

This section checks the robustness of the results obtained from the time varying parameter VARs. For brevity, not all of the robustness checks are reported, but only the ones which are considered to be relevant or show a substantially different behavior. The ones that are not reported are available upon request. Figures are shown in Appendix C.8.

Short-Run Restrictions. As mentioned, the model allows for restrictions with respect to the coefficient vector $B_{k+1,t}$ which captures the contemporaneous response of the endogenous variables to a monetary policy surprise. The time varying VARs shown above impose the restrictions that industrial production and the consumer price index do not respond contemporaneously to a monetary policy surprise. In order to check the sensitivity of the results to these assumptions, I re-estimate the Ω-VAR model without imposing such restrictions. The results remain largely unchanged and are shown in figure (50) in Appendix C.8.

Excluding the Great Recession. The findings may depend on the inclusion of the Great Recession. Figure (51) in Appendix C.8 shows the time varying impulse response functions

[42] Other papers in the literature using monetary policy surprises in order to identify the response of macro-variables to monetary policy shocks have found similar results for inflation for the 1990s (see for example Barakchian and Crowe, 2013, Thapar, 2008, and Cochrane and Piazzesi, 2002).

[43] Appendix C.10 shows the time varying IRFs in a 2D-format (percent response against the horizon of the IRF) for stock prices, CPI, and IP. In particular, the response of IP varies less over time in the short run compared to the response of stock prices. This suggests that a monetary tightening has a relatively homogeneous impact on IP in the short run across booms and recessions. Hence, large changes in the policy target rate which are needed to disinflate asset bubbles can have sizeable adverse effects on real economic activity in the short run which lead to deviations from macroeconomic targets.

for the Ω-VAR which restricts the sample to end in 2007M12. The results are much the same.

Priors. Regarding the training sample, I find that the results are unaffected for training samples which start earlier or end later. In this regard, I consider the training samples 1960M2-1990M12 and 1978M11-1994M12. Moreover, I check the robustness of the results with respect to different calibrations of κ_W, κ_S, and κ_Q. While the choices for κ_W and κ_S have little impact on the results, the choice of κ_Q does matter (as noted by Primiceri, 2005). Figure (52) in Appendix C.8 shows the time varying IRFs for the time varying Ω-VAR, but setting $\kappa_Q = 0.01$. While the results are qualitatively unchanged, setting κ_Q to a lower value decreases the time variation in the coefficients B_t which is reflected in less time variation in some of the impulse response functions.

Order of Variables. As mentioned by Primiceri (2005) with respect to the Ω_t-Model, a drawback of assuming a lower triangular reduction of Ω_t is that the order of variables in y_t may matter. I therefore check whether the results are sensitive to a re-ordering of variables. I impose the order that the financial variables appear after the slow-moving macro variables and it turns out that the results are much the same. I therefore do not report them separately.

Futures Expiring after Current Month. Barakchian and Crowe (2013) argue that a measure of shocks which combines surprises in the current month's Federal Funds future with surprises in Federal Funds futures which expire in the following months is a better indicator of exogenous changes in monetary policy, since such a measure reflects a more permanent change in monetary policy. I therefore obtain the first principal component across surprise series for the current and up to five months ahead Federal Funds futures around scheduled FOMC meetings. The first principal component across these surprise series accounts for 82% of the variance and the time varying Ω-model is re-estimated given this new surprise series. Again, the results remain largely unchanged given this new surprise series and are shown in figure (53) in Appendix C.8.

The Fed's Information Advantage. I check whether the Fed indeed only has a small information advantage over the private sector around scheduled FOMC meetings, such that the series of monetary policy surprises do not reflect the release of private information. Following Barakchian and Crowe (2013) and Gertler and Karadi (2015), the monetary surprises around scheduled FOMC meetings are orthogonalized against an empirical proxy of the Fed's private information advantage. As an empirical proxy, I use the difference between the Fed's Greenbook forecasts for output and inflation and a private sector forecasts for these variables.[44] The Greenbook forecasts are available until 2008M12 and the sample is restricted in this regard. The associated regression is reported in Appendix C.6. As noted before by Barakchian and Crowe (2013) and Gertler and Karadi (2015), the private information of the Fed around scheduled FOMC meetings seems to be small which is reflected in the fact that the empirical proxies can only explain around 12 percent in the variation of the surprises. In order to further check the sensitivity of results, the residuals from the regression in Appendix C.6 are used as the monetary surprise series for the time varying Ω-model, given that this series is orthogonal to the empirical proxy for the Fed's private information. I additionally restrict the sample to end in 2007M12, such that the last observations with respect to the Great Recession in 2008 do not distort the estimation. Compared to the earlier findings, the results remain largely unchanged and are shown in figure (54) in Appendix C.8.

Unscheduled Meetings. As mentioned above, a potential concern with respect to the identification is that the Fed has an information advantage over the private sector and it releases this information when changing interest rates. In order to address this concern, I excluded monetary surprises around *unscheduled* FOMC meetings which are likely to be affected by this concern. I check whether the results change when considering a series of monetary surprises which are obtained around *scheduled and unscheduled* FOMC meetings instead. In order to ensure that these surprises are reflecting a permanent change in monetary policy, I again take the first principal component across surprise series for the current and

[44]The survey of professional forecasters is used as a proxy for the private sector's forecast for output and inflation.

up to five months ahead Federal Funds futures (around scheduled and unscheduled FOMC meetings). The first principal component across these surprise series accounts for 87% of the variance. Given this new surprise series, I find that the time varying impulse responses are strongly affected by the Great Recession. The Ω-model is therefore instead estimated until 2007M12 and the results are reported in figure (55) in Appendix C.8. While the results are qualitatively unchanged compared the ones in the main analysis, the IRFs show less time variation since the prior for Q now has a higher impact due to the shorter sample. Setting κ_Q to higher value gives a similar time variation as the IRFs shown above.

6 Conclusion

This chapter models the economy as a time varying vector autoregression which consists of economic and financial variables. The interest lies in the time varying response of these variables to a monetary policy shock. In order to obtain such a response, a series of monetary policy surprises is extracted from Federal Funds future contracts which enters the model as an exogenous variable. The endogenous variables are allowed to react contemporaneously to these surprises and their response can vary over time since the model allows for time variation both in the coefficients with respect to the endogenous variables as well the exogenous variable.

The framework is applied to obtain evidence on the time varying response of stock prices to a monetary policy shock. I find that stock prices persistently decrease after a monetary tightening and that they decline more strongly than prices based on discounted dividends and constant risk-premia - with the difference representing an increase in risk-premia. Stock prices and risk-premia show substantial time variation in their response to monetary policy shocks. They decrease less to a monetary policy tightening during a boom or a perceived bubble period, potentially because investors are over-optimistic around this time which is reflected in a reduced responsiveness of prices. This result questions the use of “leaning against the wind policies” which aim to disinflate asset bubbles by increasing the policy target rate, since they may be ineffective if stock prices are responding by less when such policies would like them to respond. However, the policy conclusions are only suggestive and of course subject to the Lucas critique. The findings in this chapter therefore motivate a further theoretical analysis.

The framework has potentially many applications and it would be interesting to see future research which applies the model to other settings. First, the method relates to a recent identification method based on "external instruments". When such an "external instrument approach" would be considered - even outside the field of monetary policy identification - the framework in this chapter can potentially be used instead, given its advantages both with respect to constant as well as time varying parameter VARs. Second - more specific to the field of monetary policy identification - the model is suitable for systems with both economic and financial variables for which the interest lies in the time varying response of these variables to a monetary policy shock. A fruitful extension of the model would be to consider the time varying impact of forward guidance, similar to Gertler and Karadi (2015) who use monetary policy surprises with respect to future contracts which expire beyond the current month.

Chapter III

Monetary Policy & Endogenous Bubbles

1 Introduction

The recent financial crisis has reignited the debate on whether central banks should target asset bubbles, sometimes also referred to as 'leaning against the wind policies'. While opponents of such policies argue that it is difficult to identify bubbles and that monetary policy is too blunt of an instrument to deal with them (e.g. Bernanke and Gertler, 1999, 2001), advocates highlight the recent experience of the Great Recession and the potential costs of boom/bust cycles in asset prices in terms of output and price stability (e.g. ECB, 2010). However, as argued by Galí (2014), independent of one's position in this debate, what is often taken for granted, is the relation between monetary policy and bubbles. The conventional wisdom on this relation is that contractionary monetary policy is able to decrease or even pop bubbles.

Galí (2014) shows that such wisdom is in fact not supported by economic theory when considering a 'classic rational bubble'. This type of bubble is characterized by an equilibrium condition which demands that the value of the bubble today is equal to the expected present discounted value of the bubble tomorrow. Given this theory, Galí (2014) shows that contractionary monetary policy may in fact *increase* bubbles. Moreover, he finds that optimal monetary policy should *lower* interest rates if the size of a bubble becomes sufficiently large and there is a need to decrease the bubble. Furthermore, Galí and Gambetti (2015) show that these theoretical predictions are also present in the data. Given that stock prices contain a fundamental and a bubble component, a tightening of monetary policy may actually increase stock prices, if the increase in the bubble component dominates any potential decrease of the fundamental component. Imposing timing restrictions in a vector-autoregression model, Galí and Gambetti (2015) indeed find that stock prices persistently increase following contractionary monetary policy shocks. The results by Galí (2014) and Galí and Gambetti (2015) therefore call the basis of any 'leaning against the wind policies' into question.

While the empirical results by Galí and Gambetti (2015) are challenged by Paul (2015), who highlights that they depend on the considered identification of monetary policy shocks, the goal of this chapter is to show that the theoretical results by Galí (2014) depend on the theory of bubble that one considers. In this chapter, I rely on the type of bubble proposed by Miao and Wang (2015). According to this theory, a bubble may exist in firms' stock market values. If firms borrow against their stock market values, then a bubble which inflates firms' values allows to relax borrowing constraints. Compared to a classic rational bubble, the equilibrium condition that characterizes the bubble additionally includes a collateral yield. Given this theory, I find that bubbles decrease following contractionary monetary policy which additionally tightens borrowing constraints and the endogenous dynamics amplify the reaction of investment and output. Moreover, the additional amplification of investment and output is stronger, the larger the initial size of the bubble relative the economy's capital stock. These results are in contrast to the ones in Galí (2014) and in line with the conventional wisdom about the relation between monetary policy and bubbles.

Given these two theories of bubbles and the different implications that they have for the relation between monetary policy and bubbles, the question arises which theory should be favored. Recent empirical evidence by Giglio, Maggiori and Stroebel (2016) offers some guidance. Using data on residential real estate in the United Kingdom and Singapore, the authors find that transversality conditions in those markets are not violated. These findings speak against the existence of bubbles of the classic rational type which are based on a violation of the transversality condition. In contrast, within the theory of bubbles of Miao and Wang (2015), transversality conditions are not violated.

The classic rational bubble has been the workhorse model for bubbles in macroeconomics and finance. An extensive theoretical literature has shown that classic rational bubbles can occur in economies with overlapping generations (OLG). Within an OLG-model without capital, Samuelson (1958) showed that fiat money, which can be interpreted as a bubble asset, has a positive value since it can be used as a storage device and allow for wealth transfers across generations. Tirole (1985) showed that a bubble can exist in an OLG-model with capital if there is an over-accumulation of capital, such that the economy is initially dynamically inefficient and the introduction of a bubble crowds out investment and lowers the capital stock (similar to government debt in Diamond, 1965). However, empirical evidence by Abel et al. (1989) showed that the U.S. economy and several other OECD countries are dynamically efficient and episodes in which bubbles are present are usually associated with increases in investment. These concerns motivated more recent contributions. Martin and Ventura (2012) and Farhi and Tirole (2012) build models in which the introduction of a bubble can raise investment even though the economy was initially constrained dynamically efficient. In their models, bubbles help to alleviate credit frictions. The bubble in the theory by Kocherlakota (2009), which is closely related to Miao and Wang (2015), plays a similar role. In his model, land, which is intrinsically worthless, can be used as collateral and may therefore be priced positively since it allows agents to borrow and invest more. In contrast to Kocherlakota (2009) and the other mentioned contributions, the bubble in Miao and Wang (2015) exists in firms' stock market values and firms borrow against their values. Since a bubble inflates the values of firms, it relaxes borrowing constraints and raises investment and output.

A range of different approaches have been proposed in the theoretical literature on bubbles and it is out of the scope of this chapter to review this extensive literature. Instead, I refer the reader to recent surveys by Brunnermeier and Oehmke (2013) and Miao (2014). Besides the mentioned literature of bubbles which is based on OLG frictions, Brunnermeier and Oehmke (2013) differentiate existing theories based on informational frictions (e.g. Abreu and Brunnermeier, 2003), incentive distortions due to delegated investment (e.g. Allen and Gorton, 1993), credit bubbles due to risk-shifting (e.g. Allen and Gale, 2000), and heterogeneous beliefs (e.g. Scheinkman and Xiong, 2003). In addition, there also exists a literature based on irrational bubbles (e.g. Shiller, 2000). In contrast to these theories, I consider an environment with perfect information, no incentive problems associated with delegated investment or risk-shifting, homogeneous beliefs, and rational agents who have rational expectations and maximize their utility.

The rest of the chapter is organized as follows. The next section conveys the main ideas, with the help of a partial equilibrium example as in Galí (2014) and the central equations which outline the theory of Miao and Wang (2015). Section three embeds the Miao and Wang (2015) bubble within a dynamic general equilibrium model with nominal rigidities. Section four analyzes this model quantitatively. Section five concludes.

2 Intuition

I start with a partial equilibrium example of the classic rational bubble as in Galí (2014) and then illustrate how the bubble as considered in Miao and Wang (2015) differs with respect to the classic rational bubble.

Consider an economy with risk-neutral investors and an exogenous, time-varying real interest rate R_t. Further, assume there exists an infinitely-lived asset which is priced according to the following equation

$$P_t R_t = \mathbb{E}_t \left(D_{t+1} + P_{t+1} \right) \tag{26}$$

where D_{t+1} is the dividend that this asset pays in period $t+1$. If a transversality condition is not imposed, then the price P_t of this asset can be decomposed into a fundamental part and a bubble part b_t

$$P_t = \mathbb{E}_t \sum_{s=1}^{\infty} \left[\left(\prod_{j=0}^{s-1} \left(\frac{1}{R_{t+j}} \right) \right) D_{t+s} \right] + b_t$$

The fundamental part is the sum of the expected present discounted value of all future dividends. If a classic rational bubble exists, it has to satisfy the equilibrium condition that its expected growth rate is equal to the interest rate in the economy

$$\mathbb{E}_t \left[\frac{b_{t+1}}{b_t} \right] = R_t \tag{27}$$

Starting from this equation, Galí (2014) observes that an increase in the real interest R_t leads to an increase in the expected growth rate of the bubble. Moreover, if the contemporaneous decrease in b_t after an increase in R_t is small, then the increase in the expected growth rate dominates and contractionary monetary policy in fact leads to an increase in the size of a bubble. This result is in contrast to the conventional wisdom about the relation between monetary policy and bubbles which goes the other way around. Given the inherent indeterminacy of the size of the bubble b_t under the classic rational bubble theory, Galí (2014) rules out any contemporaneous effect on b_t after a change in monetary policy and finds that in an OLG model with nominal rigidities, it is in fact optimal for the monetary authority to respond with respect to the bubble by decreasing interest rates if the bubble is sufficiently large. The question arises to what extent these results depend on the theory of bubbles considered and whether other theories can confirm the results in Galí (2014).

The theory of bubble that I consider in this chapter relies on the one developed in Miao and Wang (2015). According to this theory, a bubble can exist in the stock market value of a firm which enters a borrowing constraint. Consider the simplified borrowing constraint

$$L_t \leq \mathbb{E}_t \left[\left(\frac{1}{R_t} \right) V_{t+1} \left(K_t \right) \right]$$

which states that the size of a loan L_t has to be less or equal to the expected present discounted stock market value of a firm with capital stock K_t in period $t+1$. If the stock market value takes the following form

$$V_t \left(K_t \right) = v_t K_t + b_t$$

where v_t is the value of capital and $b_t > 0$ is interpreted as a bubble since a firm without any capital would still be valued positively, then the borrowing constraint can be written as

$$L_t \leq \mathbb{E}_t \left[\left(\frac{1}{R_t} \right) \left(v_{t+1} K_t + b_{t+1} \right) \right]$$

In this economy, a bubble which inflates the stock market value of a firm helps to relax borrowing constraints. Moreover, according to this theory, the size of the bubble is determinate since it enters a borrowing constraint and a simplified version of the bubble's asset pricing equation can be written as

$$R_t = \mathbb{E}_t \left[\frac{b_{t+1} \left(1 + collateral\ yield_{t+1}\right)}{b_t} \right]$$

where the return from a bubble is given by two parts. First, a standard value part, which is the only part that is present under the classic rational bubble as considered above. Second, the bubble also provides a collateral yield since it inflates the stock market value of a firm which relaxes the borrowing constraint and allows for more investment. Rearranging the above equation and solving it forward gives

$$b_t \quad = \quad \mathbb{E}_t \left[b_{t+k} \prod_{j=1}^{k} \frac{\left(1 + collateral\ yield_{t+j}\right)}{R_{t+j-1}} \right] \quad for \;\; k = 1, 2, ...$$

Given this asset pricing equation, consider the relation between monetary policy and bubbles. Contractionary monetary policy temporarily increases real interest rates and decreases collateral yields since it becomes less profitable for firms to borrow in order to invest. As visible from the above equation, both of these effects work towards decreasing the size of the bubble. This result is in contrast to the findings by Galí (2014).

The two theories also differ with respect to whether they violate transversality conditions. Given a classic rational bubble, the transversality condition of an infinitely-lived asset as considered in (26) is violated since

$$\lim_{T \to \infty} \mathbb{E}_t \left[P_{t+T} \prod_{j=0}^{T-1} \left(\frac{1}{R_{t+j}} \right) \right] \equiv b_t \neq 0$$

Giglio, Maggiori and Stroebel (2016) use price data on residential real estate in the United Kingdom and Singapore to test whether this condition is indeed violated in practice. These real estate markets have the specific institutional setting that freehold as well as leasehold contracts are traded. Freeholds are infinite maturity ownerships and leaseholds are long-duration, finite maturity ownerships. Let P_t be the price of a freehold contract and P_t^T be the price of a leasehold contract with maturity T. Then, the above transversality condition can be approximated by[45]

$$P_t - P_t^T \approx b_t = \underset{T\to\infty}{lim}\,\mathbb{E}_t\left[P_{t+T}\prod_{j=0}^{T}(\frac{1}{R_{t+j}})\right] \quad for\ large\ T$$

where P_{t+T} is the price of the freehold contract starting in period $t+T$. The authors test whether this condition holds for leasehold contracts with a maturity of at least 700 years. They find no empirical support for the existence of a classic rational bubble when testing the failure of the above transversality condition. So whereas these findings speak against the presence of a bubble of the classic rational type, the type of bubble in this chapter cannot be ruled out based on this evidence since transversality conditions are not violated as shown in more detail below.

3 Model

Next, I formalize the above statements using a monetary general equilibrium model, augmented with a bubble as considered in Miao and Wang (2015). I consider an infinite-horizon, discrete-time production economy.

[45] Giglio, Maggiori and Stroebel (2016) in fact consider the more general version $b_t = \underset{T\to\infty}{lim}\,\mathbb{E}_t\left[\xi_{t,t+T}P_{t+T}\right]$ where $\xi_{t,t+T}$ is a stochastic discount factor between periods t and $t+T$. In accordance with the above exposition, I consider the special case for which $\xi_{t,t+T} = \prod_{j=0}^{T-1}(\frac{1}{R_{t+j}})$.

3.1 Household

Following Greenwood, Hercowitz and Huffman (1988), the representative household values consumption C_t and dislikes labor N_t captured by the flow utility

$$U\left(C_t, N_t\right) = \frac{1}{1-\gamma}\left(C_t - \frac{N_t^{1+\phi}}{1+\phi}\right)^{1-\gamma}$$

where ϕ represents the inverse Frisch elasticity of labor supply. The household chooses contingent plans for consumption, labor supply, firm stocks s_t, and savings, in the form of a one-period and riskless bond B_t, so as to maximize lifetime utility, while discounting the future at the rate β. Taking prices, wages, and interest rates as given, the household solves the problem

$$V^H\left(B_{t-1}, s_{t-1}^j, \mathbb{S}_t\right) = \max_{C_t, N_t, B_t, s_t^j}\left\{U\left(C_t, N_t\right) + \beta\mathbb{E}[V^H\left(B_t, s_t^j, \mathbb{S}_{t+1}\right)]\right\}$$

subject to

$$\begin{aligned} C_t + B_t + \int p_t^j s_t^j dj &\leq w_t N_t + B_{t-1}R_t + \int s_{t-1}^j (p_t^j + d_t^j) + T_t \\ \mathbb{S}_t &= \Gamma(\mathbb{S}_{t-1}) \end{aligned}$$

where w_t is the real wage and R_t the real interest rate. The stock of firm j is valued at the real price p_t^j per unit and d_t^j is the dividend per unit of stock. $\Gamma(.)$ denotes the law of motion for aggregate state variables $\mathbb{S}_t$ and the expectation $\mathbb{E}\left[.\right]$ is formed conditional on the information set $\mathbb{S}_t$ at time t. Moreover, the household receives a lump-sum transfer T_t from firms. The solution to the above problem gives the inter- and intratemporal optimality conditions

$$w_t = N_t^{\phi}$$

$$1 = \mathbb{E}\left[\Lambda_{t,t+1} R_{t+1}\right]$$

$$1 = \mathbb{E}\left[\Lambda_{t,t+1}\left(\frac{p_{t+1}^j + d_{t+1}^j}{p_t^j}\right)\right]$$

where $\Lambda_{t,t+1} = \beta \left(\frac{C_{t+1} - \frac{N_{t+1}^{1+\phi}}{1+\phi}}{C_t - \frac{N_t^{1+\phi}}{1+\phi}} \right)^{-\gamma}$ is the household's stochastic discount factor.

3.2 Firms

A continuum of firms operate according to a Cobb-Douglas production function

$$Y_t^{j,m} = (K_t^j)^\alpha (N_t^j)^{1-\alpha}$$

in order to produce an intermediate good $Y_t^{j,m}$ by combining labor supplied by the household with capital K_t^j which is chosen in period $t-1$. After solving the static labour choice problem, taking the real wage as given, operating profits are

$$R_t^K K_t^j = \max_{N_t^j} \; P_t^m (K_t^j)^\alpha (N_t^j)^{1-\alpha} - w_t N_t^j$$

where R_t^K depends only on the aggregate wage and the aggregate intermediate good price P_t^m and is given by

$$R_t^K = \alpha (P_t^m)^{\frac{1}{\alpha}} \left(\frac{w_t}{(1-\alpha)} \right)^{\frac{\alpha-1}{\alpha}}$$

Following Kiyotaki and Moore (1997) and Miao and Wang (2015), firms face idiosyncratic investment opportunities. With probability π, an investment opportunity arrives. The capital stock of firm j therefore evolves as

$$K_{t+1}^j = \begin{cases} K_t^j (1-\delta) & with \; (1-\pi) \\ K_t^j (1-\delta) + I_t^j & with \; \pi \end{cases}$$

Before the arrival of an investment opportunity, each firm chooses its dividend payout D_t^j, its investment I_t^j, and its borrowings L_t^j from the household in case an investment opportunity arrives. Firms cannot borrow intertemporally, but only *intra*-temporally. These loans are taken up at the beginning of the period and repaid at the end. Firms do not pay interest on their intra-period loans and issue new stocks $s_t^{j,new}$ at the end of period t in order to repay their intra-period loans, such that $p_t s_t^{j,new} = L_t^j$.

The market value $V_t(K_t^j, \mathbb{S}_t)$ of each firm prior to the arrival of an investment opportunity is given by the solution to the following problem

$$V_t(K_t^j, \mathbb{S}_t) = \max_{I_t^j, L_t^j, D_t^j} \pi \left\{ R_t^K K_t^j - I_t^j + \mathbb{E}\left[\Lambda_{t,t+1} V_{t+1}\left(K_t^j(1-\delta) + I_t^j, \mathbb{S}_{t+1}\right)\right]\right\} \tag{28}$$
$$+ (1-\pi)\left\{ R_t^K K_t^j + \mathbb{E}\left[\Lambda_{t,t+1} V_{t+1}\left(K_t^j(1-\delta), \mathbb{S}_{t+1}\right)\right]\right\}$$

subject to

$$D_t^j + I_t^j \leq R_t^K K_t^j + L_t^j \tag{29}$$
$$D_t^j \geq 0 \tag{30}$$
$$L_t^j \leq \mathbb{E}\left[\Lambda_{t,t+1} V_{t+1}(\xi K_t^j, \mathbb{S}_{t+1})\right] \tag{31}$$
$$\mathbb{S}_t = \Gamma(\mathbb{S}_{t-1}) \tag{32}$$

Constraint (29) is a budget constraint. It states that the firm's profits and its intra-period loan have to cover its dividend payouts and investment. Constraint (30) is a restriction on raising equity which reflects the cost of raising external funds. Without this constraint, firms would reach a state in which they could fully self-finance, circumvent constraint (31), and a bubble could not exist.

Constraint (31) is a borrowing constraint. The constraint follows the specification in Miao and Wang (2015) and is at the center of the model. It states that the intra-period loan L_t^j cannot exceed the expected present discounted stock market value of the reorganized firm in period $t+1$. It is assumed that the borrowing constraint arises from an agency problem (similar to Hart and Moore, 1994, Kiyotaki and Moore, 1997, and Diamond and Rajan, 2000). Assume the firm is run by a manager who cannot commit to contributing his human capital.

At the end of period t, when a firm needs to repay its intra-period loan, the manager of the firm may try to renegotiate the debt contract, threatening to withdraw his human capital. It is assumed that the firm manager has all the bargaining power in the debt renegotiation. The firm manager can offer alternative contracts and the household can either accept or reject those offers. If the renegotiation fails, the household can take over the reorganized firm in period $t + 1$. Due to costs associated with the reorganization of the firm, the household is only able to recover a fraction ξ of the capital stock, where $0 < \xi < 1$. Given the recovered capital stock ξK_t^j, the household is then able to operate the reorganized firm which is valued at $V_{t+1}(\xi K_t^j, \mathbb{S}_{t+1})$ in period $t + 1$. The expected present discounted value of the reorganized firm in period t is given by $\mathbb{E}\left[\Lambda_{t,t+1} V_{t+1}(\xi K_t^j, \mathbb{S}_{t+1})\right]$, which is termed the 'threat value'. During the debt renegotiation at the end of period t, the firm manager is able to renegotiate the amount of debt outstanding down until the threat value is reached. Ex-ante, at the beginning of period t, a household would therefore never lend more than the threat value, since a firm can always renegotiate its debt down to the threat value. This gives rise to the borrowing constraint (31).

3.3 Monetary Policy & Price-Stickiness

The monetary authority controls the short-term nominal interest rate according to the policy rule

$$i_t = (1 - \rho^m)(i^{SS} + \phi_\pi log \Pi_t) + \rho^m i_{t-1} + \epsilon_t^m \tag{33}$$

where i^{SS} is a constant, Π_t is the rate of inflation from period $t-1$ to period t, and $0 < \rho^m < 1$ reflects the desire of the monetary authority to smooth interest rates. The only source of aggregate risk in the model enters via equation (33), where $\epsilon_t^m \sim N(0, \sigma_m^2)$ is a monetary policy shock. The real interest rate is determined by the Fischer equation

$$R_{t+1}\mathbb{E}\left[\Pi_{t+1}\right] = (1 + i_t)$$

Another step in the production process is introduced, similar to the specification in Gertler and Karadi (2011) and Christiano, Eichenbaum and Evans (2005), to include price stickiness which gives rise to a non-neutrality of monetary policy. Retailers purchase and repackage intermediate goods and sell their output to a representative final good producer who assembles the retailer's output and sells the final good Y_t. The final output good Y_t is a CES-composite of a continuum of mass unity of differentiated retail firms' output

$$Y_t = \left(\int_0^1 Y_{j,t}^{\frac{(\epsilon-1)}{\epsilon}} dj \right)^{\frac{\epsilon}{(\epsilon-1)}} \tag{34}$$

where $Y_{j,t}$ is the produced output of retailer j. The final output producer minimizes its costs

$$\underset{Y_{j,t}}{min}\; P_t Y_t - \int_0^1 P_{j,t} Y_{j,t} dj$$

subject to equation (34). The minimization problem yields the following demand function for retail goods

$$Y_{j,t} = \left(\frac{P_{j,t}}{P_t} \right)^{-\epsilon} Y_t \tag{35}$$

Retailers are subject to price rigidities. Every period, a fraction θ of firms cannot adjust their price. Firms that are allowed to adjust, choose their optimal price P_t^* solving the following problem

$$\underset{P_t^*}{max}\; \mathbb{E} \left[\sum_{i=0}^{\infty} \theta^i \beta^i \Lambda_{t,t+i} \left[\frac{P_t^*}{P_{t+i}} - P_{m,t+i} \right] Y_{f,t+i} \right] \tag{36}$$

subject to equation (35). The first-order condition arising from this problem can be written in recursive form, using two auxiliary forward-looking variables F_t and Z_t which are stated in Appendix D.2, together with the dispersion of prices Δ_t.

3.4 Firm Stock Market Value

The firms' decision problem does not give a contraction mapping and allows for multiple solutions. I therefore follow Miao and Wang (2015) and conjecture that the stock market value takes the form

$$V_t(K_t^j, \mathbb{S}_t) = v_t K_t^j + b_t \tag{37}$$

where v_t is the value of capital and b_t is the size of the bubble. Both v_t and b_t depend on the aggregate states $\mathbb{S}_t$. There exists a solution in which $b_t > 0$, which is interpreted as a bubble since the stock market value of a firm without any capital ($K_t^j = 0$) is still positive. However, there may also be a second solution to the firms' problem in which $b_t = 0$, such that a bubble does not exist. In this case, the firms' market value is given by

$$V_t(K_t^j, \mathbb{S}_t) = v_t K_t^j$$

I assume that bubbles can be freely discarded and therefore do not consider the case for which $b_t < 0$.

3.5 Equilibrium Dynamics

Next, suppose that it is profitable for firms to invest. Then, the expected present discounted value of another unit of capital $\mathbb{E}\left[\Lambda_{t,t+1} v_{t+1}\right]$, Tobin's marginal Q, is larger than its cost, i.e.

$$\mathbb{E}\left[\Lambda_{t,t+1} v_{t+1}\right] > 1$$

where the cost of investment is equal to one since consumption goods can be converted into investment goods one-for-one. Under the above condition, firms would want to invest the maximal possible amount and pay out as little dividends as possible in case an investment opportunity arrives. Thus, for firms with an investment opportunity, the minimal dividend payout constraint (30) and the borrowing constraint (31) bind

$$L_t^j = \mathbb{E}\left[\Lambda_{t,t+1} V_{t+1}(\xi K_t^j, \mathbb{S}_{t+1})\right] \tag{38}$$

$$I_t^j = R_t^K K_t^j + L_t^j \tag{39}$$

$$D_t^j = 0 \tag{40}$$

In contrast, firms without an investment opportunity do not take up a loan and pay out all of their profits as dividends, since they cannot save inter-temporally

$$L_t^j = I_t^j = 0$$

$$D_t^j = R_t^K K_t^j$$

Substituting equations (38) and (39), as well as (37) into the firms' market value (28), and matching coefficients gives two asset pricing equations which are summarized in Proposition 1, together with the evolution of the aggregate capital stock $K_t = \int_0^1 K_t^j dj$.

Proposition 1. *Suppose* $\mathbb{E}\left[\Lambda_{t,t+1} v_{t+1}\right] > 1$*, then the equilibrium sequences* (b_t, v_t, K_{t+1}) *for* $t = 0, 1, 2, ...$ *satisfy*

$$v_t = R_t^K + \mathbb{E}\left[\Lambda_{t,t+1} v_{t+1}(1-\delta) + \pi(\Lambda_{t,t+1} v_{t+1} - 1)(\Lambda_{t,t+1} v_{t+1} \xi + R_t^K)\right] \tag{41}$$

$$b_t = \mathbb{E}\left[\Lambda_{t,t+1}\left\{b_{t+1} + \pi(\Lambda_{t,t+1} v_{t+1} - 1) b_{t+1}\right\}\right] \tag{42}$$

$$K_{t+1} = K_t(1-\delta) + \pi\left(\mathbb{E}\left[\Lambda_{t,t+1}(v_t K_t + b_t)\right] + R_t^K K_t\right) \tag{43}$$

and the transversality conditions are

$$\lim_{T\to\infty} \mathbb{E}\left[\Lambda_{t,t+T} v_T K_T\right] = 0 \;, \quad \lim_{T\to\infty} \mathbb{E}\left[\Lambda_{t,t+T} b_T\right] = 0$$

The asset pricing equation for capital, equation (41), takes a standard form. The value of capital in period t is determined by the contemporaneous return R_t^K, as well as the expected present discounted value of capital in period $t+1$ (net of depreciation) and the collateral yield that it provides. Another unit of capital relaxes the borrowing constraint (31) by an amount $\Lambda_{t,t+1}v_{t+1}\xi$ which happens with probability π and gives the additional benefit of investment $(\Lambda_{t,t+1}v_{t+1}-1)$. Additionally, firms with an investment opportunity can use their contemporaneous internal funds $R_t^K K_t$ to invest. The collateral yield of a unit of capital is therefore given by $\Lambda_{t,t+1}\pi(\Lambda_{t,t+1}v_{t+1}-1)(v_{t+1}\xi+R_t^K)$.

The value of the bubble in period t is determined by the expected present discounted value of two components, the value of the bubble in period $t+1$ and a collateral yield. A positive bubble in period t is supported since it persists in period $t+1$ which relaxes the borrowing constraint (31) by an amount $\Lambda_{t,t+1}b_{t+1}$. The relaxation of the borrowing constraint through the inflated stock market value gives the benefit from investment $(\Lambda_{t,t+1}v_{t+1}-1)$ in case an investment opportunity arrives which happens with probability π. The collateral yield of the bubble is therefore given by $\Lambda_{t,t+1}\pi(\Lambda_{t,t+1}v_{t+1}-1)b_{t+1}$. Proposition 1 also allows for the solution in which $b_t=0$.

Under the classic rational bubble theory, a bubble does not provide a collateral yield and the asset pricing equation for b_t reduces to[46]

$$b_t = \mathbb{E}\left[\Lambda_{t,t+1}b_{t+1}\right]$$

and the transversality condition is violated since

$$\lim_{T\to\infty} \mathbb{E}\left[\Lambda_{t,t+T}b_T\right] = b_t$$

In contrast, under the theory of bubbles in this chapter, the bubble additionally pays a collateral yield which lowers the necessary growth rate of the bubble. The transversality condition is

[46] In equation (27), I consider the special case in which $\Lambda_{t,t+1} = (\frac{1}{R_t})$.

therefore not violated. The empirical evidence by Giglio, Maggiori and Stroebel (2016) shows that transversality conditions are not violated in practice. These findings therefore speak against the existence of bubbles of the classic rational type, whereas the theory of bubbles in this chapter cannot be ruled out based on this evidence.

3.6 Steady States

In what follows, I analyze economies in which it is always profitable for firms with an investment opportunity to invest and therefore the borrowing constraint and the minimum dividend payout constraint bind for investing firms according to (38) and (39). Given these constraints, I consider the conditions under which a bubble and a no-bubble steady state can exist. Proposition 2 gives the condition for the existence of a bubble in steady state.

Proposition 2. *In a bubble steady state it holds that $b > 0$.*
If $0 < \xi < \delta(\frac{1}{\pi} - 1) + 1 - \frac{1}{\beta}$, there exists a deterministic bubble steady state which satisfies

$$\begin{aligned}
\frac{b}{K} &= \frac{\delta}{\pi} - R^K - \beta v \xi > 0 \\
\beta v &= \left[\left(\frac{1}{\beta} - 1\right)\frac{1}{\pi} + 1\right] > 1 \\
R^K &= \frac{v\left(1 - \beta(1-\delta) - \pi(\beta v - 1)\beta\xi\right)}{1 + \pi(\beta v - 1)}
\end{aligned}$$

and equations (38) and (39) hold for investing firms.
Derivation: see Appendix D.1.

The intuition behind Proposition 2 is as follows. If ξ, the fraction of the capital stock that a household can recover during the reorganization of a firm, is sufficiently low, then the borrowing constraint (31) is tight enough, such that a bubble allows to relax the borrowing constraint. The collateral yield that a bubble provides is then high enough, such that the value of the bubble can remain constant in steady state and the bubble is valued positively since it provides a collateral yield.

Moreover, the existence of a bubble is only influenced by the probability of investment π, the depreciation rate δ, and the household's discount rate β. Hence, the conduct of monetary policy does not influence the existence of a bubble. However, monetary policy does influence the dynamics of the bubble away from steady state.

Proposition 3 gives the conditions for the existence of a steady state in which no bubble is present.

Proposition 3. *In a no-bubble steady state it holds that* $b = 0$.
If $0 < \xi < \delta(\frac{1}{\pi} - 1) + 1 - \frac{1}{\beta}$, *there exists a deterministic no-bubble steady state which satisfies*

$$\beta v = \frac{\delta(\frac{1}{\pi} - 1)}{\frac{1}{\beta} + \xi - 1} > 1$$
$$R^K = \frac{\delta}{\pi} - \beta v \xi$$

and equations (38) and (39) hold for investing firms.
Derivation: see Appendix D.1.

3.7 Competitive Equilibrium

Denote aggregate labour demand as $N_t = \int_0^1 N_t^j dj$ and average investment among investing firms as I_t. Goods markets clear according to

$$\begin{aligned} C_t + \pi I_t &= Y_t \\ K_{t+1} &= (1-\delta)K_t + \pi I_t \end{aligned}$$

Under the condition that it is profitable for firms to invest (Proposition 1), the equilibrium conditions of the model for $t = 0, 1, ..., \infty$ are listed in Appendix D.2 and summarized by

$$\mathbb{E}[G(\mathbb{S}_t, X_t, \mathbb{S}_{t+1}, X_{t+1})] = 0 \quad (44)$$

where X_t is a vector of non-state variables and $\mathbb{S}_t = \{K_t, \Delta_{t-1}, \rho^m i_{t-1} + \epsilon_t^m\}$ is a vector of aggregate state variables. A solution of the model is given by a set of policy functions $\hat{S}_{t+1} = f_{\mathbb{S}}(\mathbb{S}_t)$ and $X_t = f_X(\mathbb{S}_t)$ where $\hat{S}_t = \{K_t, \Delta_{t-1}\}$ are the endogenous state variables. I solve for these policy functions using a first-order perturbation method around a deterministic steady state.

4 Quantitative Analysis

4.1 Calibration

The model is calibrated to quarterly frequency for the U.S. economy. The calibration is summarized in Table 6.[47] Most of the parameters are taken directly from the calibration in Gertler and Karadi (2011). For brevity, I do not further discuss these choices. The parameters specific to this model are the probability of an investment opportunity π and the fraction of recovery in case of a reorganization of the firm ξ. I discuss the calibration choices of these parameters next.

[47]The inflation coefficient in the Taylor rule results from solving the constrained optimal social planner problem

$$\max_{\phi_\pi} \int V^H(\mathbb{S}_t) dF^{\mathbb{S}} \approx \sum_{t=1}^{T} \frac{V^H(\mathbb{S}_t)}{T}$$

subject to

$$i_t = (1-\rho^m)(i^{SS} + \phi_\pi log\Pi_t) + \rho^m i_{t-1} + \epsilon_t^m$$

where $dF^{\mathbb{S}}$ is the ergodic distribution of the state and $T = 100.000$ is used in the approximation. The standard deviation of the monetary policy shock is set to $\sigma_m = 0.15\%$ which is calibrated to the quarterly standard deviation of surprise monetary policy shocks as obtained by Kuttner (2001). I check after each simulation whether the conditions under which Proposition 1. was derived were indeed satisfied for all periods.

Description	*Parameter*	*Value*	*Source / Target*
Probability investment opportunity	π	*0.18*	*Cooper and Haltiwanger (2006)*
Recovery fraction in reorganization	ξ	*0.025*	*Existence bubble*
Risk aversion household	γ	*2*	*Standard*
Discount factor household	β	*0.99*	*Standard*
Inverse Frisch elasticity of labor supply	ϕ	*0.276*	*Gertler and Karadi (2011)*
Effective capital share	α	*0.33*	*Gertler and Karadi (2011)*
Depreciation rate	δ	*0.025*	*Gertler and Karadi (2011)*
Elasticity of substitution	ϵ	*4.167*	*Gertler and Karadi (2011)*
Price stickiness	θ	*0.779*	*Gertler and Karadi (2011)*
Inflation coefficient Taylor rule	ϕ_π	*1.13*	*Constrained optimal policy*
Smoothing parameter Taylor rule	ρ_m	*0.8*	*Gertler and Karadi (2011)*
Constant term in Taylor rule	i^{SS}	$\frac{1}{\beta}-1$	*deterministic SS*

Table 6: ***Calibration.*** *Calibration of structural parameters.*

The calibration of the probability of an investment opportunity π is complicated by the fact that even very small new purchases to the capital stock of firms, such as a new pen for example, can be seen as investments. I therefore calibrate π to the percentage of firms which show sufficiently high investment rates (defined as $\frac{I_t}{K_t}$). Using micro firm level data, Cooper and Haltiwanger (2006) report that around 18% of U.S. firms show investment rates of 20% or higher and I calibrate π according to this number.

The fraction of recovery in case of a reorganization of the firm ξ is calibrated such that a bubble exists in a deterministic steady state of the model. Recall from Proposition 2 that a deterministic bubbly steady state exists if $0 < \xi < \delta(\frac{1}{\pi} - 1) + 1 - \frac{1}{\beta}$ where the upper bound $\delta(\frac{1}{\pi} - 1) + 1 - \frac{1}{\beta} = 0.1$ under the above calibration. Since this condition gives a range for the parameter ξ, I initially set ξ to 0.025 and then vary the parameter in the quantitative analysis below in order to understand how this changes the results.

4.2 Steady State Comparison

Given the baseline calibration, Table 7 gives the steady state values of several variables in the bubble economy and the no-bubble economy. The bubble relaxes the borrowing constraint of firms and therefore alleviates agency problems in the economy. Investment, the capital stock, output, and consumption are therefore higher in the bubble economy compared to the no-bubble economy. Moreover, the existence of the bubble increases the household's welfare in steady state. In this regard, the presence of the bubble improves the economy.

Description	*Variable*	*Bubble Economy*	*No-Bubble Economy*
Bubble	b	2.5	0
Investment	πI	1.2	0.6
Capital Stock	K	49.4	25.7
Value of capital	v	1.1	1.9
Output	Y	7.1	4.5
Consumption	C	5.9	3.9
Welfare	V^H	-32.8	-48.1

Table 7: ***Steady State Comparison.*** *Bubble vs. No-Bubble Economy.*

4.3 Impulse Response Functions

This section analyzes the dynamics of the bubble economy around its deterministic steady state. Figure (21) shows impulse response functions to a 100 basis point contractionary monetary policy shock. The blue, solid lines indicate the percentage deviations from steady state for variables in the bubble economy and the orange, dashed lines show the percentage deviations from steady state in an economy which is equivalent in all respects, except that the bubble is held constant at its steady state value. The two economies are therefore equivalent with respect to their steady states. However, they may differ in their dynamics away from steady state and any difference is due to the endogenous response of the bubble.[48] Figure (21) shows that after an increase in the nominal interest rate i_t, the size of the bubble b_t decreases on impact and then returns to its steady state level. The intuition for this result is as follows. After contractionary monetary policy, due to price rigidities and monopolistic competition among retailers, it is beneficial for firms to decrease their output. The benefit from investment, the value of capital, and future collateral yields therefore decline. The value of the bubble decreases since it is positively related to future values of capital and collateral

[48]For the constant bubble economy, I re-optimize the coefficient on inflation in the Taylor rule as described in footnote (47).

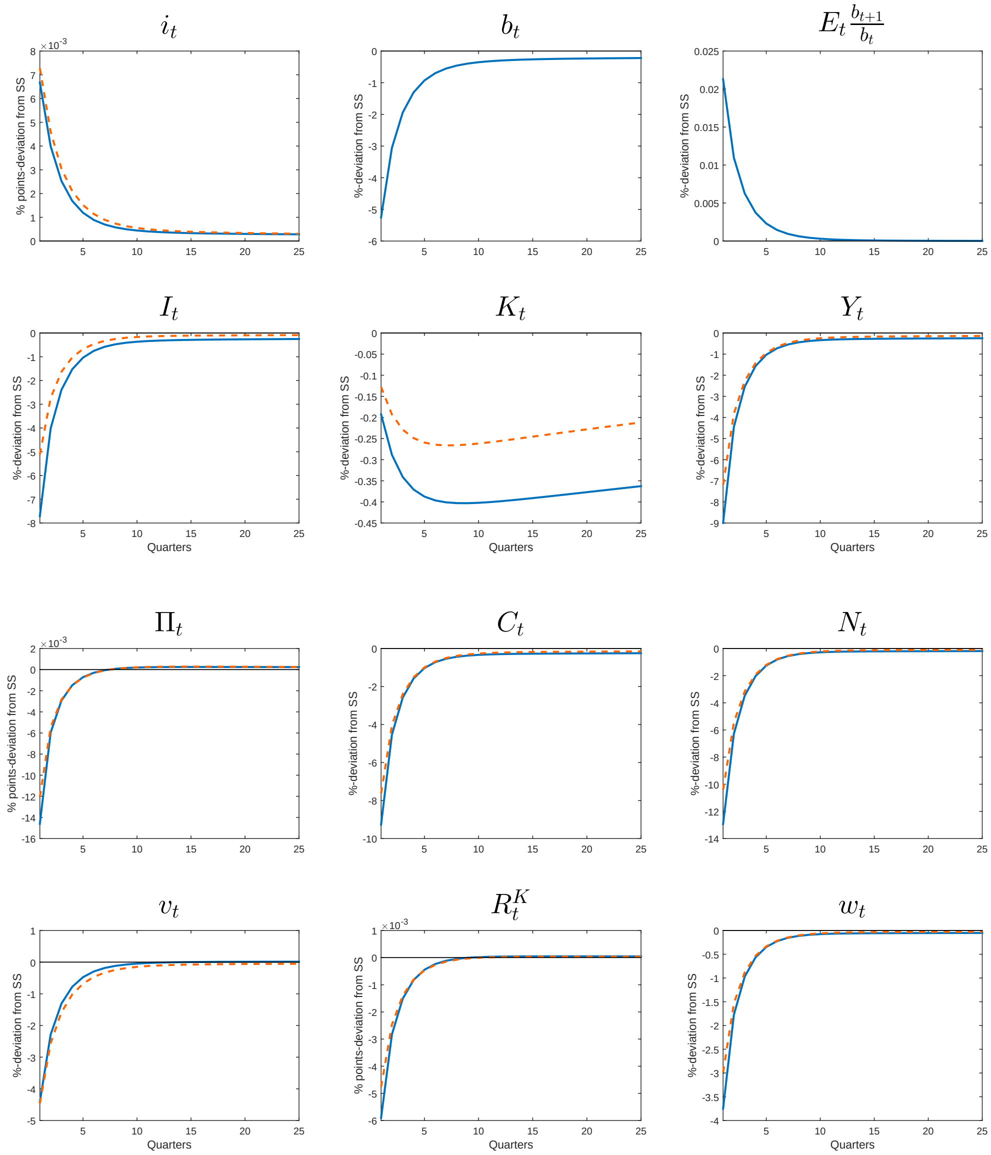

Figure 21: ***Impulse response functions.*** *IRFs to a 100 basis point contractionary monetary policy shock. Blue, solid: Endogenous Bubble Economy. Orange, dashed: Constant Bubble Economy.*

yields, which becomes visible by solving the asset pricing equation of the bubble (42) forward

$$b_t = \mathbb{E}\left[\Lambda_{t,t+1}\left(\underbrace{b_{t+1}}_{value} + \underbrace{\pi(\Lambda_{t,t+1}v_{t+1} - 1)b_{t+1}}_{collateral\ yield}\right)\right]$$

$$= \mathbb{E}\left[\Lambda_{t,t+k}b_{t+k}\prod_{j=0}^{k-1}\left((1-\pi) + \pi\Lambda_{t+j,t+j+1}v_{t+j+1}\right)\right] \quad for \;\; k = 1, 2, ...$$

where $\Lambda_{t,t+k}$ is the household's stochastic discount factor between periods t and $t+k$.

Bubble accelerator. Given the decrease in the value of the bubble and the associated tightening of the borrowing constraint after a contractionary monetary policy shock, the initial percentage deviations from steady state of investment, capital, output, consumption, hours, and inflation are larger in the endogenous bubble economy vs. the constant bubble economy. The bubble therefore acts as an accelerator additional to the standard financial accelerator (Bernanke, Gertler and Gilchrist, 1999) which is working via the decreased capital values, and which is present in the constant bubble economy. Figure (22) shows how the magnitude of the amplification depends on the parameter ξ. Figure (22) plots the difference in the percentage deviation from steady state between the endogenous bubble and the constant bubble economy for different values of ξ, holding all other parameters constant (so the difference between the IRFs in Figure (21)). The amplification of investment, capital, output, consumption, hours, and inflation is stronger, the smaller ξ. The intuition for this result is that ξ governs the size of the economy's bubble relative to the aggregate capital stock. Given the equation for the steady state bubble-to-capital ratio as stated in Proposition 2, the smaller ξ, the larger the size of the bubble relative to the economy's capital stock in steady state and hence the stronger the amplification via the bubble. Moreover, the amplification via the endogenous dynamics of the bubble is also quantitatively important. For example, for a calibration of $\xi = 0.05$, output decreases by around 1.2% more in the endogenous bubble economy vs. an economy in which the bubble is held constant at its steady state value following a 100 basis point contractionary monetary policy shock.

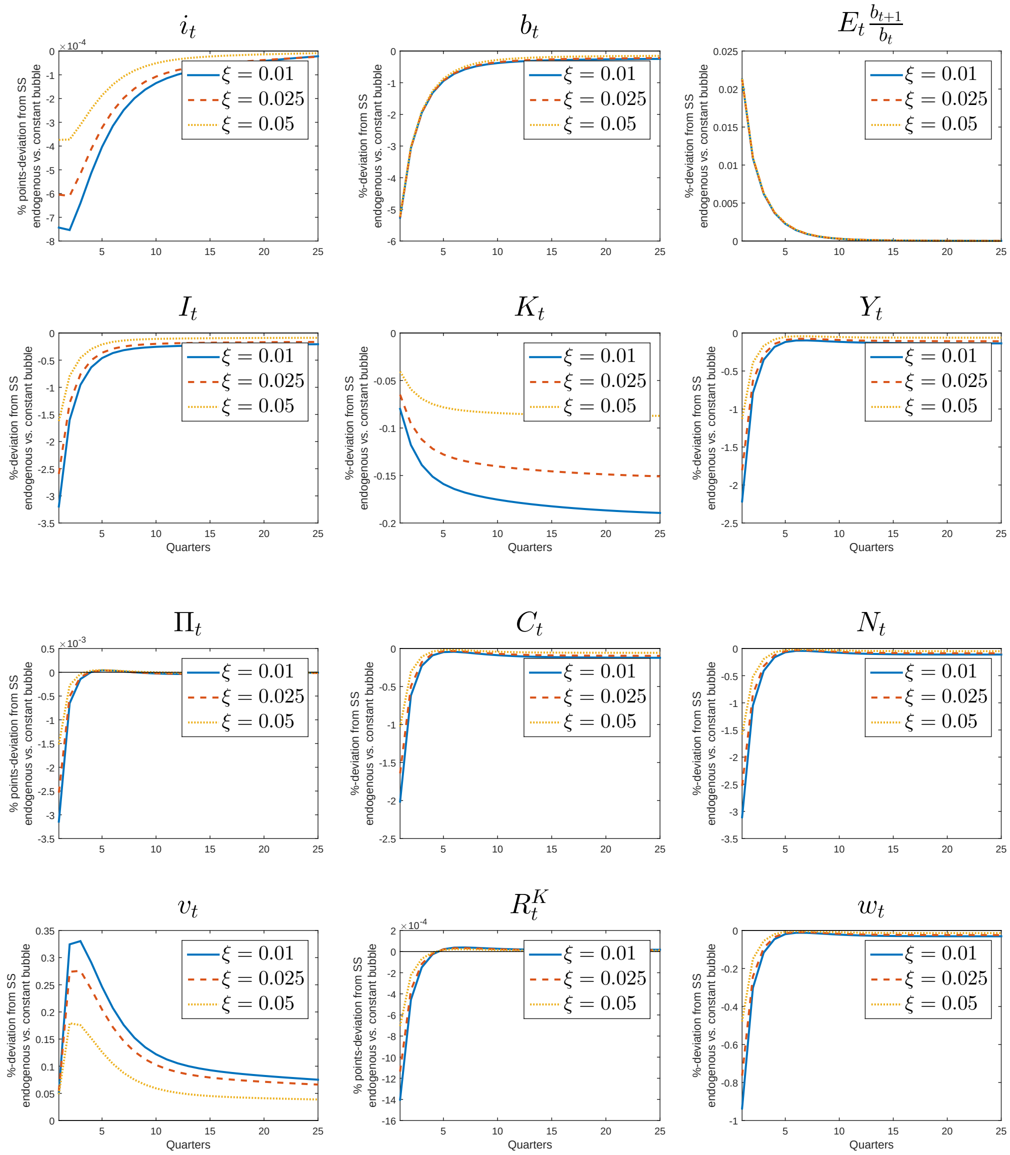

Figure 22: ***Impulse Response Functions.*** *Difference in percentage deviations from steady state between the endogenous bubble economy and the constant bubble economy to a 100 basis point contractionary monetary policy shock.*

Discussion. As visible from the IRFs, the value of the bubble co-moves with fundamental values which enter the stock market value of a firm. To illustrate the difference to the theory of classic rational bubbles further, note that in equilibrium the aggregate flow of dividends from the firm sector to the household could be priced according to[49]

$$M_t = D_t + E_{\mathbb{S}}\left[\Lambda_{t,t+1} M_{t+1}\right] \tag{45}$$

where the aggregate dividends D_t are equal to firm profits minus the cost of investment

$$D_t = R_t^K K_t - \pi I_t$$

Moreover, it holds in equilibrium that the aggregate firm value is equal to the present discounted value of all future dividends

$$V_t(K_t, \mathbb{S}_t) = v_t K_t + b_t = M_t$$

Recall that a classic rational bubble arises as another solution of an asset pricing equation like (45) if transversality conditions are not imposed[50]. In contrast, the bubble by Miao and Wang (2015) can exist because it relaxes borrowing constraints and allows firms to invest more. As visible from the above equation, the bubble manifests itself in an increased flow of dividends D_t from the household to the firm sector.

Another question is whether one should actually mind the presence of such a bubble? In this chapter, the bubble improves the economy by easing agency frictions and increases welfare. In this regard, the answer is no. However, the bursting of the bubble is associated with a tightening of borrowing constraints and a drop of output and consumption (Miao and Wang, 2015). Moreover, the bubble could also retard growth if it arises in less productive sectors and causes a capital reallocation to these sectors (Miao and Wang, 2014).

[49]The contemporaneous dividends are included in this asset pricing equation in order to to be in accordance with the timing assumption of $V_t(K_t, \mathbb{S}_t)$.

[50]As shown in equations (26) to (27).

5 Conclusion

This chapter considered a monetary dynamic general equilibrium model, augmented with a bubble as proposed Miao and Wang (2015). Within this framework, a bubble can be present in the stock market value of a firm which enters a firm's borrowing constraint. Given this theory, I analyze the impact of monetary policy on the bubble. I find that expansionary monetary policy leads to an increase in the size of the bubble which relaxes firms' borrowing constraints and amplifies the reaction of investment, capital, and output towards a monetary policy shock. The larger the steady state value of the bubble compared to the economy's capital stock, the stronger is this amplification.

My results are in contrast to the ones in Galí (2014). He considers a bubble of the classic rational type and given this theory of bubbles, he finds that contractionary monetary policy can in fact increase the size of bubbles. My aim was to highlight that these results strongly depend on the theory of bubbles that one considers and further research is needed before this line of research influences policy considerations.

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A Appendix to Chapter I

A.1 Derivations

A.1.1 Incentive Compatibility Constraint

The entrepreneur's objective function (4) under the good project can be rewritten as

$$V_t^{good} = (1-\gamma)\mathbb{E}\left[\sum_{j=1}^{\infty}\Lambda_{t,t+j}\left\{\gamma^{j-1}R_{t+j}^K Q_{t+j-1}^K K_t^{new}\int_{\overline{\omega}_{t+j|t}}^{1+b}\left(\omega-\overline{\omega}_{t+j|t}\right)d\Phi(\omega)+\frac{\gamma^j}{1-\gamma}r_{t+j}^K K_t^{new}\right\}\right]$$

since

$$L_t^{new} = R_{t+j}^K Q_{t+j-1}^K K_t^{new}\overline{\omega}_{t+j|t} \quad for\ j \geq 1$$

where cumulative distribution function and partial expectation under the uniform distribution for $\omega \sim U[1-b, 1+b]$ are

$$\Phi(\overline{\omega}_{t+j|t}) = \frac{\overline{\omega}_{t+j|t}-(1-b)}{2b} \tag{46}$$

$$\int_{\overline{\omega}_{t+j|t}}^{1+b}\omega d\Phi(\omega) = \frac{1}{4b}\left((1+b)^2-\overline{\omega}_{t+j|t}^2\right) \tag{47}$$

and

$$\int_{\overline{\omega}_{t+j|t}}^{1+b}(\omega-\overline{\omega}_{t+j|t})d\Phi(\omega) = \frac{1}{2b}\left(\frac{1}{2}(1+b)^2+\frac{1}{2}\overline{\omega}_{t+j|t}-\overline{\omega}_{t+j|t}(1+b)\right)$$

Using these definitions, one can show that the value function can be expressed as

$$V_t^{good} = (1-\gamma)\left(K_t^{new}J_t^g - L_t^{new}G_t^g + \frac{(L_t^{new})^2}{K_t^{new}}S_t^g\right)$$

where J_t^g, G_t^g, and S_t^g are three 'forward-looking' auxiliary variables which are defined as

$$\begin{aligned}
J_t^g &= \mathbb{E}\left[\Lambda_{t,t+1}\left\{\frac{(1+b)^2}{4b}R_{t+1}^K Q_t^K + r_{t+1}^K\frac{\gamma}{1-\gamma} + \gamma J_{t+1}^g\right\}\right] \\
G_t^g &= \mathbb{E}\left[\Lambda_{t,t+1}\left\{\frac{(1+b)}{2b} + \gamma G_{t+1}^g\right\}\right] \\
S_t^g &= \mathbb{E}\left[\Lambda_{t,t+1}\left\{\frac{1}{4b}\frac{1}{R_{t+1}^K Q_t^K} + \gamma S_{t+1}^g\right\}\right]
\end{aligned}$$

One can show that the value function under the bad project has a similar representation. Taking these representations together, the continuously binding IC constraint can be expressed as in equations (54)-(57) in Appendix A.2.

A.1.2 Return on Market Portfolio of Loans

The return on the market portfolio of loans is given by equation (10) and repeated here

$$R_t^L = \frac{\gamma Q_t + (1-\gamma)\frac{1}{L_{t-1}}\left\{\sum_{j=1}^{\infty}\left(1-\Phi(\overline{\omega}_{t|t-j})\right)\gamma^{j-1}L_{t-j}^{new} + (1-\mu)\sum_{j=1}^{\infty}\left[\int_{1-b}^{\overline{\omega}_{t|t-j}}\omega R_t^K Q_{t-1}^K \gamma^{j-1}K_{t-j}^{new}d\Phi(\omega)\right]\right\}}{Q_{t-1}}$$

Using the definition of the cumulative distribution function in (46), one can show that

$$\sum_{j=1}^{\infty}\left(1-\Phi(\overline{\omega}_{t|t-j})\right)\gamma^{j-1}L_{t-j}^{new} = (\frac{1+b}{2b})L_{t-1} - \frac{1}{2bR_t^K Q_{t-1}^K}x_{t-1}$$

where

$$\begin{aligned}
L_{t-1} &= L_{t-1}^{new} + \gamma L_{t-2} \\
x_{t-1} &= \frac{(L_{t-1}^{new})^2}{K_{t-1}^{new}} + \gamma x_{t-2}
\end{aligned}$$

and using the definition of the partial expectation given in (47), one can show that

$$\sum_{j=1}^{\infty}\left[\int_{1-b}^{\overline{\omega}_{t|t-j}}\omega R_t^K Q_{t-1}^K\gamma^{j-1}K_{t-j}^{new}d\Phi(\omega)\right] = \frac{1}{4b}\frac{1}{R_t^K Q_{t-1}^K}x_{t-1} - \frac{(1-b)^2}{4b}R_t^K Q_{t-1}^K K_{t-1}$$

where

$$K_{t-1} = K_{t-1}^{new} + \gamma K_{t-2}$$

Taking these together, the profits per loan can be written as

$$R_t^L Q_{t-1} = \gamma Q_t + (1-\gamma)\left\{\frac{1+b}{2b} - (1-\mu)\frac{(1-b)^2}{4b}\frac{R_t^K Q_{t-1}^K}{L_{t-1}}K_{t-1} - \frac{x_{t-1}(1+\mu)}{4bR_t^K Q_{t-1}^K L_{t-1}}\right\}$$

Using a similar reasoning, one can show that the evolution of net worth for new entrepreneurs can be expressed as

$$N_t = (1-\gamma)\left\{\frac{(1+b)^2}{4b}R_t^K Q_{t-1}^K K_{t-1} - \frac{1+b}{2b}L_{t-1} + \frac{1}{4b}\frac{x_{t-1}}{R_t^K Q_{t-1}^K}\right\}$$

A.2 Model Equations

This section outlines the model equations for **both the real and the nominal model** (outlined in Appendix B) in a parsimonious way. The real version of the model is obtained by setting $\Pi_t = P_t^m = \Delta_t = 1 \;\; \forall \;\; t$ and omitting the subsection *"Monetary Policy & Price Stickiness"*.

Household & Good Producer

$$\mathbb{E}\left[\Lambda_{t,t+1} R_{t+1}\right] = 1 \tag{48}$$

$$\Lambda_{t,t+1} = \beta^H \left(\frac{C_t - \chi\frac{H_t^{1+\phi}}{1+\phi}}{C_{t+1} - \chi\frac{H_{t+1}^{1+\phi}}{1+\phi}}\right) \tag{49}$$

$$(1-\alpha)P_t^m \frac{Y_t}{\Delta_t} = \chi H_t^{1+\phi} \tag{50}$$

$$Y_t = \Delta_t e^{a_t} K_{t-1}^{\alpha} H_t^{1-\alpha} \tag{51}$$

$$a_t = \rho_a a_{t-1} + \epsilon_t^a \tag{52}$$

Entrepreneurs

$$Q_t^K K_t^{new} = N_t + Q_t L_t^{new} \tag{53}$$

$$0 = \left(K_t^{new} J_t - L_t^{new} G_t + \frac{(L_t^{new})^2}{K_t^{new}} S_t \right) \tag{54}$$

$$J_t = \mathbb{E}\left[\Lambda_{t,t+1} \left\{ \left(\frac{(1+b)^2}{4b} - \frac{(\widetilde{k}+\widetilde{c})^2}{4\widetilde{c}} \right) R_{t+1}^K Q_t^K + \gamma J_{t+1} \right\} \right] \tag{55}$$

$$G_t = \mathbb{E}\left[\Lambda_{t,t+1} \left\{ \left(\frac{1+b}{2b} - \frac{\widetilde{k}+\widetilde{c}}{2\widetilde{c}} \right) \frac{1}{\Pi_t} + \gamma \frac{1}{\Pi_t} G_{t+1} \right\} \right] \tag{56}$$

$$S_t = \mathbb{E}\left[\Lambda_{t,t+1} \left\{ \left(\frac{1}{4b} - \frac{1}{4\widetilde{c}} \right) \frac{1}{\Pi_t^2 R_{t+1}^K Q_t^K} + \gamma \frac{1}{\Pi_t^2} S_{t+1} \right\} \right] \tag{57}$$

$$N_t = (1-\gamma) \left\{ \frac{(1+b)^2}{4b} R_t^K Q_{t-1}^K K_{t-1} - \frac{(1+b)}{2b} \frac{L_{t-1}}{\Pi_t} + \frac{1}{4b} \frac{x_{t-1}}{\Pi_t^2 R_t^K Q_{t-1}^K} \right\} \tag{58}$$

Financial Intermediary

$$D_t + Q_t L_t + B_{t-1} R_t = B_t + \frac{R_t^L}{\Pi_t} Q_{t-1} L_{t-1} \tag{59}$$

$$\mathbb{E}\left[\frac{R_{t+1}}{D_{t+1}} \right] + \lambda_t = \mathbb{E}\left[\frac{1}{D_{t+1}} \frac{R_{t+1}^L}{\Pi_{t+1}} \right] \tag{60}$$

$$L_t = L_t^{new} + \gamma \frac{L_{t-1}}{\Pi_t} \tag{61}$$

$$K_t = K_t^{new} + \gamma K_{t-1} \tag{62}$$

$$x_t = \frac{(L_t^{new})^2}{K_t^{new}} + \gamma \frac{x_{t-1}}{\Pi_t^2} \tag{63}$$

$$R_t^L Q_{t-1} = \gamma Q_t + (1-\gamma)[\frac{1+b}{2b} \tag{64}$$

$$-(1-\mu) \frac{\Pi_t}{L_{t-1}} \frac{(1-b)^2}{4b} R_t^K Q_{t-1}^K K_{t-1} - \frac{1}{4b} \frac{x_{t-1}(1+\mu)}{R_t^K Q_{t-1}^K \Pi_t^2}] \tag{65}$$

Occasional Financial Crises

If $\frac{B_t}{Q_t L_t} \leq \kappa$ or $r_{t-1} = 1$

$$\lambda_t = 0$$

If $\frac{B_t}{Q_t L_t} > \kappa$ and $r_{t-1} = 0$

$$B_t = \overline{\tau}(D_t^{unc} + Q_t^{unc} L_t^{new,unc}) + B_{t-1}R_t - \frac{R_t^L}{\Pi_t} Q_{t-1}L_{t-1} + Q_t \gamma \frac{L_{t-1}}{\Pi_t}$$

Capital Producers and Resource Constraint

$$Q_t^K = 1 + \zeta(\frac{K_t}{K_{t-1}} - 1) \quad (66)$$

$$Y_t = C_t + D_t + K_t - (1-\delta)K_{t-1} + \frac{\zeta}{2}\left(\frac{K_t}{K_{t-1}} - 1\right)^2 K_{t-1} + \quad (67)$$

$$(1-\gamma)\mu \left(\frac{1}{4b}\frac{x_{t-1}}{\Pi_t^2 R_t^K Q_{t-1}^K} - \frac{(1-b)^2}{4b} R_t^K Q_{t-1}^K K_{t-1}\right) \quad (68)$$

$$R_t^K Q_{t-1}^K = \left(Q_t^K(1-\delta) + \alpha P_t^m \frac{Y_t}{\Delta_t K_{t-1}}\right) \quad (69)$$

Monetary Policy & Price Stickiness (only present in the nominal model)

$$i_t = (1-\rho^m)\left(i^{SS} + \phi_\pi log \Pi_t + \phi_y log\left(\frac{\epsilon - 1}{\epsilon P_t^m}\right)\right) + \rho^m i_{t-1} + \epsilon_t^m \quad (70)$$

$$\frac{F_t}{Z_t} = \frac{\epsilon - 1}{\epsilon}\left(\frac{1-\theta\Pi_t^{\epsilon-1}}{(1-\theta)}\right)^{\frac{1}{1-\epsilon}} \quad (71)$$

$$F_t = P_t^m Y_t + \mathbb{E}\left[\theta \Lambda_{t,t+1} \Pi_{t+1}^{\epsilon} F_{t+1}\right] \quad (72)$$

$$Z_t = Y_t + \mathbb{E}\left[\theta \Lambda_{t,t+1} \Pi_{t+1}^{\epsilon-1} Z_{t+1}\right] \quad (73)$$

$$\Delta_t = \left((1-\theta)\left(\frac{1-\theta\Pi_t^{\epsilon-1}}{(1-\theta)}\right)^{-\frac{\epsilon}{1-\epsilon}} + \theta\frac{\Pi_t^{\epsilon}}{\Delta_{t-1}}\right)^{-1} \quad (74)$$

$$R_t = \frac{(1+i_{t-1})}{\Pi_t} \quad (75)$$

A.3 Solution Technique

Given the definition of a solution in Section 4.6, I describe next how the policy functions $\hat{S}_{t+1} = f_{\hat{S}}(\mathbb{S}_t)$ and $X_t = f_X(\mathbb{S}_t)$ are obtained using a projection algorithm. Broadly, this involves three choices. First, one has to choose a grid on which the model is solved. Second, one has to decide on the parametrization of the policy functions. Third, given an initial parametrization, one has to choose an iteration procedure. These three choices structure the description below.

Grid. The model is solved on a Smolyak sparse grid due to the curse of dimensionality (Bellman, 1961). The construction of the Smolyak sparse grid works as follows. The grid points in the space $[-1, 1]$ for each state variable are obtained by tensor-products of nested sets of Chebyshev extrema and the application of the Smolyak rule for a given level of approximation which controls how many of these tensor-products are included in the grid (see also Malin, Krueger and Kubler, 2011). I select 5 for the level of approximation, giving 2433 grid points for the five state variables (excluding r_{t-1}). Next, the grid points are transformed from the space $[-1, 1]$ into the relevant space given the model's calibration. In order to determine the relevant space, I solve the model first with a third-order perturbation method around a deterministic steady state (ignoring the occasionally-binding constraint), simulate it for $500,000$ periods, and choose the 2.5%- and 97.5%-percentiles as the lower L_B and upper U_B bounds for each state variable.[51] A linear transformation $(x+1)\frac{(U_B - L_B)}{2} + L_B$ is used to transform each grid point x from $[-1, 1]$ into $[L_B, U_B]$, giving the full set of grid points $j = 1, ..., M$ in the relevant state space. The grid on which the model is solved remains fixed during the iteration on the policy functions (see Maliar and Maliar (2015) for an alternative method).

Parametrization of policy functions. I parametrize several non-state variables using third-order ordinary polynomials. In particular, let X_t^P be a parametrized variable where $X_t^P \in \{K_t^{new}, \frac{1}{D_t}, R_{t+1}, J_t, S_t, G_t\}$ and let r_t be an indicator function determining whether there is a creditor run in period t, in which case $r_t = 1$, or not, such that $r_t = 0$. Then, $X_t^P(\mathbb{S}_t)$ is parametrized using the piecewise flexible form with separate coefficients $\beta_{r_t=0}^X$ and

[51] I slightly perturb the model by adding a small risk-premium on debt for the financial intermediary which depends on the level of debt. This gives a unique portfolio choice in a deterministic steady state and allows to solve the model with standard perturbation methods around this deterministic steady state (see for example Schmitt-Grohe and Uribe (2003) for similar techniques with respect to small-open economy models). The third-order perturbation solution also serves as a first guess for coefficients in the parametrized policy functions. During the iteration to obtain a global solution, the risk-premium is sequentially reduced until it reaches zero (see also chapter 5.9. on "Homotopy Methods" in Judd, 1998, in this regard). I thank Fabrice Collard for a discussion on this topic.

$\beta^X_{r_t=1}$

$$X^P_t(\mathbb{S}_t) = (1 - r_t)\beta^X_0 T(\mathbb{S}_t) + r_t\beta^X_1 T(\mathbb{S}_t) \tag{76}$$

where $T(\mathbb{S}_t)$ is a vector collecting the basis functions. The number of grid points is larger than the number of coefficients. Hence, the outlined solution algorithm does not give an exact solution on the grid points such as in collocation methods (see for example Malin, Krueger and Kubler, 2011).[52]

Iteration. Given an initial guess for the coefficients β^X_0 and β^X_1, the iteration proceeds as follows.

1. Obtain the vector collecting the basis functions $T(\mathbb{S}_{t,j})$ for a given grid point j. Assume that there is no creditor run in period t and calculate the parametrized variables $X^P_{t,j}(\mathbb{S}_{t,j}; r_t = 0)$ via (76). Substitute $X^P_{t,j}(\mathbb{S}_{t,j}; r_t = 0)$ into the set of equations summarized in Appendix A.2. Using the equilibrium conditions, solve for the rest of the variables and set the lagrange multiplier $\lambda_t = 0$. Check whether the financial intermediary's leverage exceeds the threshold κ. If so, go back to the beginning, set $r_t = 1$, use the parametrization $X^P_{t,j}(\mathbb{S}_{t,j}; r_t = 1)$ instead, and additionally add the constraint $B_t = \tau(\mathbb{S}_{t,j})$. This separates the grid points into two sets: a set of points for which there is no creditor run and a set for which there is a creditor run. When there is a creditor run, K^{new}_t is not parametrized, but given by the equilibrium conditions. Instead, the intertemporal equation (13) is used to check that the lagrange multiplier λ_t is positive.

2. Having solved for all period t variables at grid point j, one obtains next period's endogenous state variables $\hat{S}_{t+1,j}$. In order to approximate integrals arising from expectation operators in intertemporal equations, I use nine Hermite-Gaussian quadrature nodes and weights for period $t+1$. This gives next period's exogenous state variables $\overline{S}_{t+1,j,i}$ and therefore $\mathbb{S}_{t+1,j,i}$ for each node $i \in \{1, 2, ..., 9\}$ in period $t+1$ and each grid point j. As-

[52] A collocation method cannot be applied since the number of grid points for which a creditor run occurs may change during the iteration procedure.

sume that there is no creditor run in period $t+1$ at node i for grid point j. Use again the initial parametrization $X^P_{t+1,j,i}(\mathbb{S}_{t+1,j,i}; r_{t+1} = 0)$ and solve for the rest of the variables at node i in period $t+1$. If $r_t = 0$, check whether the financial intermediary's leverage in period $t+1$ exceeds threshold κ. If so, use the parametrization $X^P_{t+1,j,i}(\mathbb{S}_{t+1,j,i}; r_{t+1} = 1)$ instead, and additionally add the constraint $B_{t+1} = \tau(\mathbb{S}_{t+1,j,i})$.

3. Having solved for all period $t+1$ variables, compute the expectation integrals appearing in the model's equations. The intertemporal equations give an estimate $X^{P*}_{t,j}(\mathbb{S}_{t,j})$ for each of the initially parametrized variables $X^P_{t,j}(\mathbb{S}_{t,j})$ at each grid point j. A fixed-point is obtained when the initially assumed value $X^P_{t,j}(\mathbb{S}_{t,j})$ is equal to $X^{P*}_{t,j}(\mathbb{S}_{t,j})$.

4. Until a fixed point is reached, iterate over the coefficients β^X_0 and β^X_1 in the policy functions (76). Collect the vectors of basis functions $T(\mathbb{S}_{t,j})$ for all grid points for which there is no creditor run in period t, combine them in a matrix $T_0(\mathbb{S}_t)$ and project these on the obtained estimates $X^{P*}_{t,j}(\mathbb{S}_{t,j})$, giving

$$\hat{\beta}^X_0 \equiv \left(T_0(\mathbb{S}_t)' T_0(\mathbb{S}_t)\right)^{-1} T_0(\mathbb{S}_t)' X^{P*}_{t|r_t=0}$$

where $X^{P*}_{t|r_t=0}$ is a vector collecting the obtained estimates $X^{P*}_{t,j}(\mathbb{S}_{t,j})$ for which there is no creditor run. Repeat the same for all grid points for which there is a creditor run in period t, resulting in

$$\hat{\beta}^X_1 \equiv \left(T_1(\mathbb{S}_t)' T_1(\mathbb{S}_t)\right)^{-1} T_1(\mathbb{S}_t)' X^{P*}_{t|r_t=1}$$

5. Compute the coefficients $\beta^{X'}_0$ and $\beta^{X'}_1$ which are used for the next iteration via

$$\begin{aligned} \beta^{X'}_0 &= (1-\xi)\hat{\beta}^X_0 + \xi\beta^X_0 \\ \beta^{X'}_1 &= (1-\xi)\hat{\beta}^X_1 + \xi\beta^X_1 \end{aligned}$$

where $0 < \xi < 1$ is a dampening parameter which makes convergence more likely ($\xi = 0.1$ is used).

6. Check for convergence and end iteration if

$$\frac{1}{6}\sum_{X_t^P\in A}\frac{1}{M-Mb}\sum_{j=1}^{M}\left|\frac{X_{t,j}^{P*}-X_{t,j|r_t=0}^{P}}{X_{t,j|r_t=0}^{P}}\right| \quad < \quad \eta$$

and

$$\frac{1}{5}\sum_{X_t^P\in A'}\frac{1}{Mb}\sum_{j=1}^{M}\left|\frac{X_{t,j}^{P*}-X_{t,j|r_t=1}^{P}}{X_{t,j|r_t=1}^{P}}\right| < \eta$$

7. where $A = \{K_t^{new}, \frac{1}{D_t}, R_{t+1}, J_t, S_t, G_t\}$, $A' = A \backslash K_t^{new}$, and Mb denotes the number of binding coefficients which may change while iterating. $\eta = 5^{-04}$ is used.[53]

Given the policy functions $X_t^P(\mathbb{S}_t)$, one can use the model's equations to obtain the full set of policy functions $\hat{S}_{t+1} = f_{\hat{S}}(\mathbb{S}_t)$ and $X_t = f_X(\mathbb{S}_t)$ for a solution of the model as given in Definition 1.

A.4 Accuracy

Besides having an accurate solution on the grid points, I check whether the solution is also accurate at other points in state space. The accuracy of the solution is confirmed by analyzing the absolute residual equation errors

$$\left|\frac{X_t^{P*}-X_t^P}{X_t^P}\right| \tag{77}$$

in a simulation of the model as suggested by Judd (1992), see also Bocola (2015) for a similar analysis. X_t^{P*} is obtained as described in Appendix A.3. I simulate the model for $500,000$ periods and compute the decimal log of the absolute residual equation errors for each period t and for each $X_t^P \in \{K_t^{new}, \frac{1}{D_t}, R_{t+1}, J_t, S_t, G_t\}$. In Figure (23), I plot histograms of those errors for each parametrized variable, where red lines indicate means.

[53] I find that setting η to a lower value does not strongly increase the accuracy of the solution away from the grid points or change any of the results, but results in an increase in computational time.

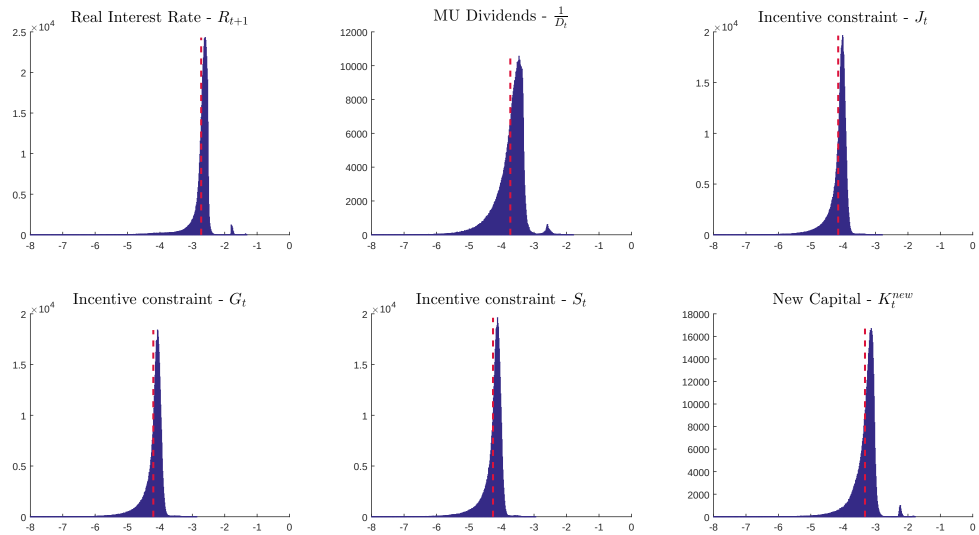


Figure 23: ***Accuracy.*** *Histograms for absolute residual equation errors in decimal log basis, based on a simulation for 500,000 periods. Red lines indicate means.*

The means all lie around -3.5. Given the reasoning in (Judd, 1992), one can consider the solution to be accurate. Since I am particularly interested in obtaining an accurate solution at points for which the occasionally-binding constraint holds and a financial crisis occurs, I report the decimal log of the absolute residual equation errors at those points separately in Figure (24). As can be seen, the solution is still very accurate in the state space where financial crises occur which lies far away from the steady state of the model. Moreover, the lagrange multiplier λ_t on the debt constraint is always positive during financial crises. I conclude that the outlined solution algorithm gives an accurate *nonlinear global solution* of the model, both in the state space in which "standard business cycles" occur, as well as in the region in which the economy experiences a financial crisis.

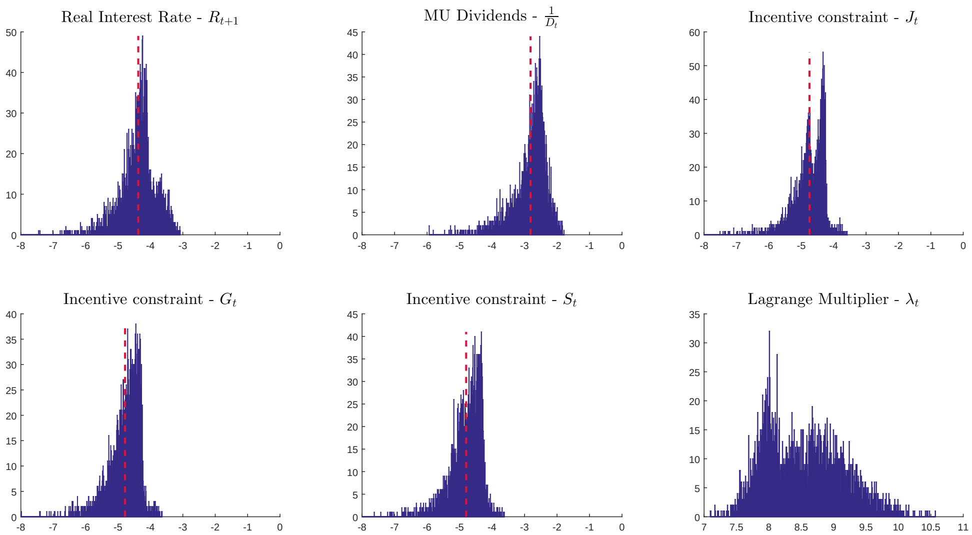


Figure 24: ***Accuracy.*** *Histograms for absolute residual equation errors in decimal log basis at points during which the economy experiences a financial crisis, based on a 500,000 periods simulation of the model. Red lines indicate means.*

A.5 Stochastic Steady State

Description	***Variable***	***Value***	***Description***	***Variable***	***Value***
Consumption	C_{SS}	1.77	*Asset-to-Equity-Ratio*	$\frac{Q_{SS}L_{SS}}{Q_{SS}L_{SS}-B_{SS}}$	1.92
Hours	H_{SS}	0.96	*Dividends*	D_{SS}	0.02
Output	Y_{SS}	2.13	*Return to loans*	R^L_{SS}	1.01
Capital	K_{SS}	13.86	*Loans*	L_{SS}	2.31
Return capital	R^K_{SS}	1.02	*Net worth*	N_{SS}	1.10
New loans	$Q_{SS}L^{new}_{SS}$	0.18	*Price long-term debt*	Q_{SS}	0.83

Table 8: ***Stochastic Steady State.*** *Value of endogenous variables at the stochastic steady state of the real model.*

A.6 Median Target Financial Crisis

In the spirit of Fry and Pagan (2011), this section reports the "Median Target Financial Crisis". The paths around this crisis are obtained by selecting the crisis, for which the sequence of shocks is 'closest' to the median shock sequence in Figure (10) before a financial crisis occurs. The closest sequence of shocks is the one which minimizes a distance criterion. Denote $\tilde{\epsilon}^a_{t-k}$

the size of the shock k quarters before the financial crisis which occurs at time t, $med(\tilde{\epsilon}^a_{-k})$ the median and $std(\tilde{\epsilon}^a_{-k})$ the standard deviation across the shock sequences k quarters before a crisis. The "Median Target Financial Crisis" is the one which minimizes $\sum_{k=0}^{30}\left(\frac{\tilde{\epsilon}^a_{t-k}-med(\tilde{\epsilon}^a_{-k})}{std(\tilde{\epsilon}^a_{-k})}\right)^2$. The shocks occurring after the crisis are set to zero and the paths around the "Median Target Financial Crisis" are compared to the median paths in Figures (10) and (11).

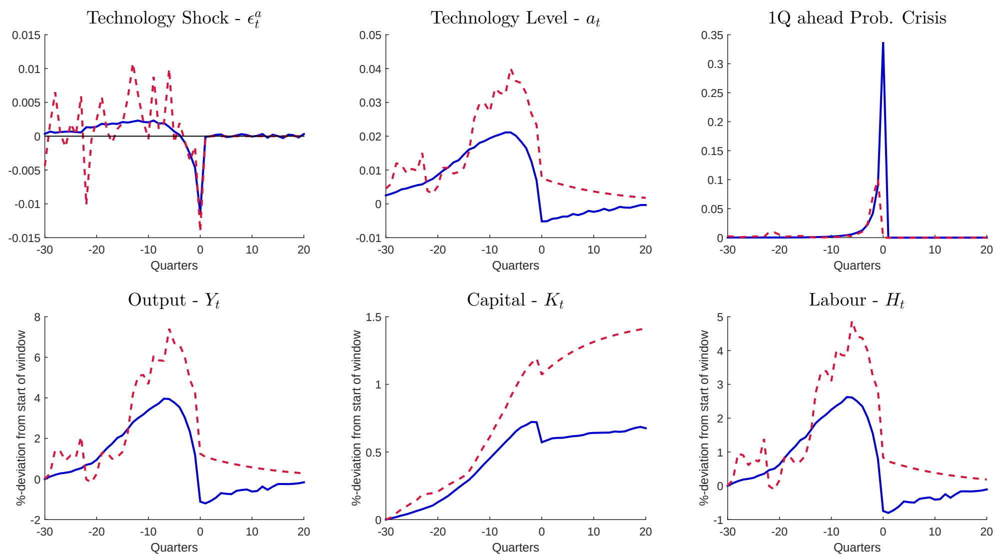


Figure 25: ***Median Target Financial Crisis vs. Typical Financial Crises.*** *Event window around "Median Target Financial Crisis" (red, dotted line) or median path of the typical financial crisis (blue, solid line) at Quarter = 0.*

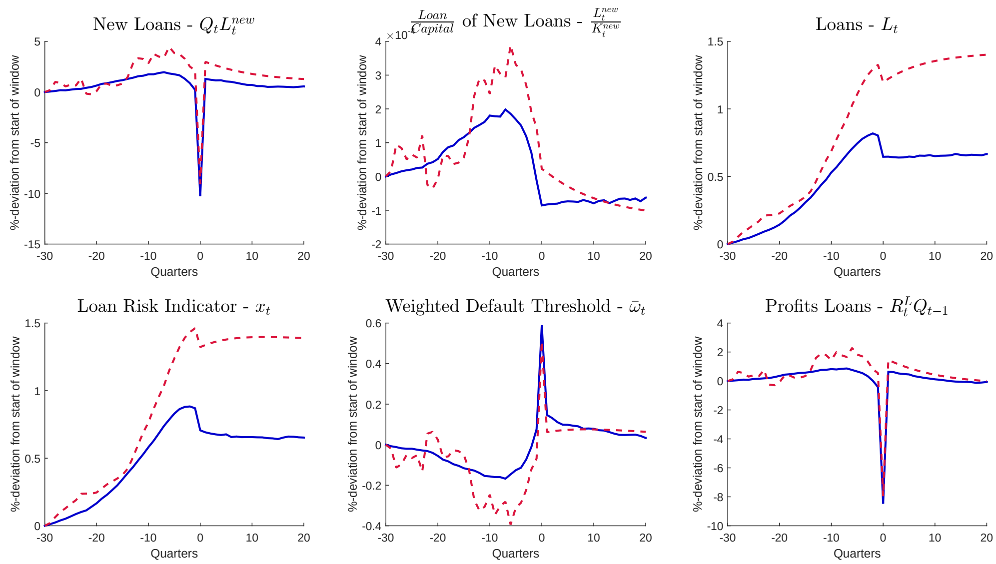


Figure 26: ***Median Target Financial Crisis vs. Typical Financial Crises.*** *Event window around "Median Target Financial Crisis" (red, dotted line) or median path of the typical financial crisis (blue, solid line) at Quarter = 0.*

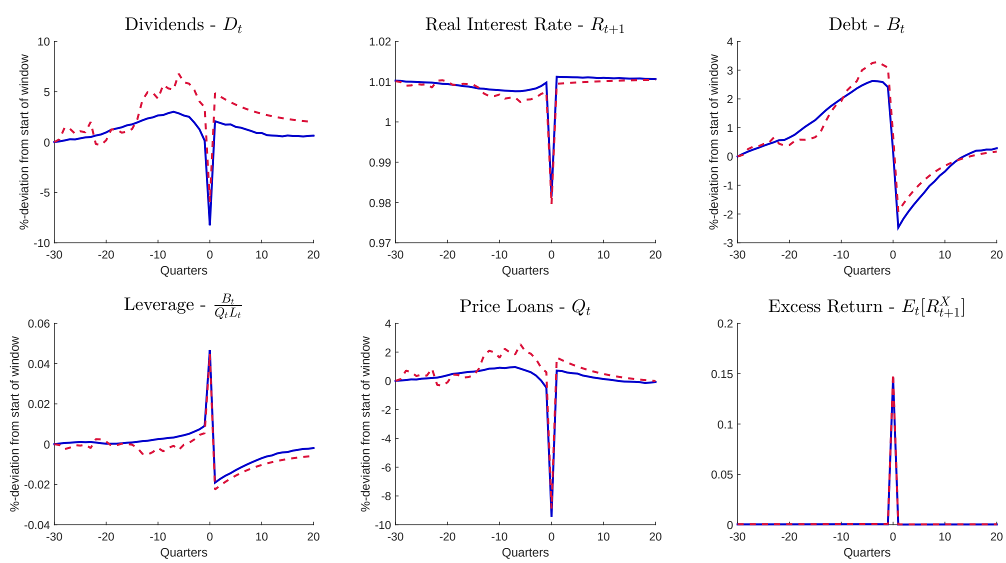


Figure 27: ***Median Target Financial Crisis vs. Typical Financial Crises.*** *Event window around "Median Target Financial Crisis" (red, dotted line) or median path of the typical financial crisis (blue, solid line) at Quarter = 0.*

A.7 Typical Non-Financial Recessions

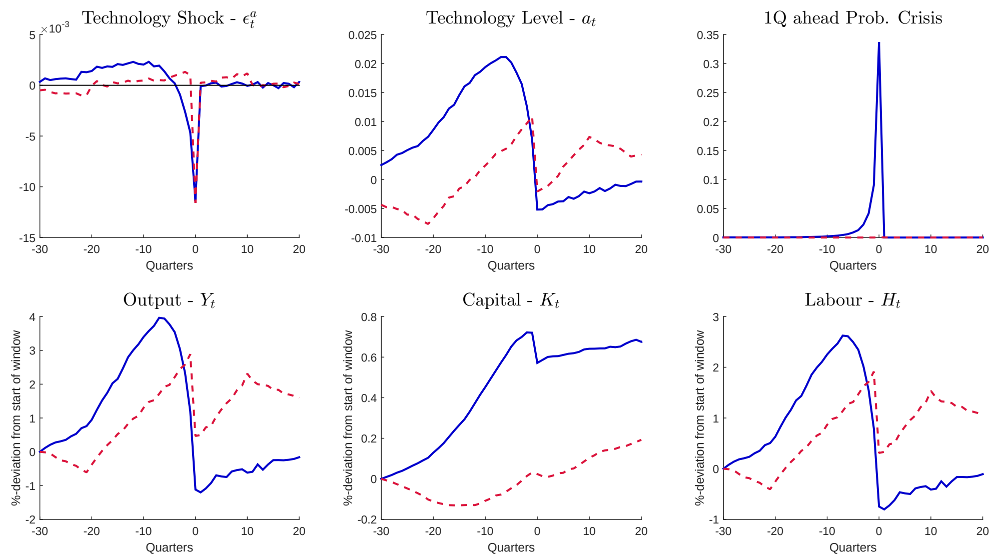


Figure 28: ***Typical Non-Financial Recessions vs. Financial Crises.*** *Event window around non-financial recession (red, dotted line) or financial crisis (blue, solid line) at Quarter = 0. Based on a simulation of 500,000 periods. Median paths are shown.*

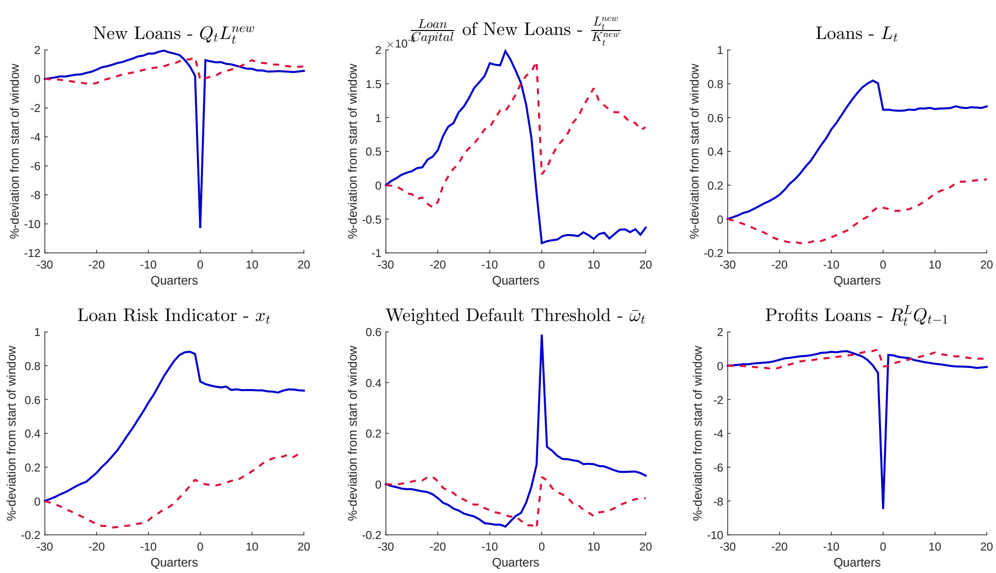


Figure 29: ***Typical Non-Financial Recessions vs. Financial Crises.*** *Event window around non-financial recession (red, dotted line) or financial crisis (blue, solid line) at Quarter = 0. Based on a simulation of 500,000 periods. Median paths are shown.*

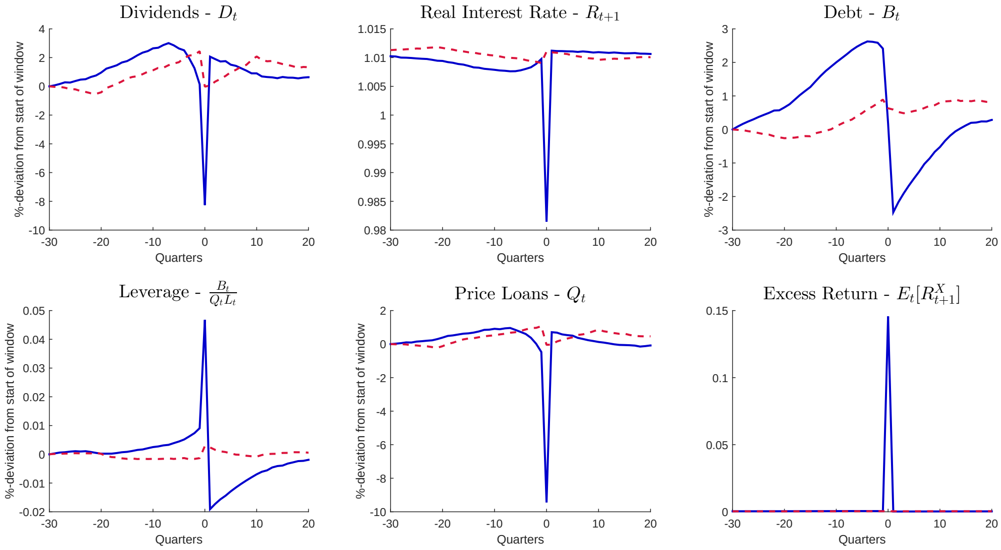


Figure 30: ***Typical Non-Financial Recessions vs. Financial Crises.*** *Event window around non-financial recession (red, dotted line) or financial crisis (blue, solid line) at Quarter = 0. Based on a simulation of 500,000 periods. Median paths are shown.*

A.8 Replicating Schularick & Taylor (2012)

	OLS	OLS + GDP	OLS	OLS + GDP
Constant	0.0052***	0.0052***	0.0052***	0.0052***
$\Delta log(L_{t-1})$	1.5997***	1.6088***	0.3362***	0.5013***
$\Delta log(L_{t-2})$	1.3147***	1.3974***	0.4518***	0.6525***
$\Delta log(L_{t-3})$	0.8391***	1.2668***	0.3859***	0.7361***
$\Delta log(L_{t-4})$	0.2898***	0.5714***	0.2155***	0.4776***
$\Delta log(L_{t-5})$	0.4508***	−0.0618	0.3171***	0.1522***
Book Value Loans			X	X
5 lags GDP growth		X		X

Table 9: *The dependent variable is a dummy - indicating whether there has been a creditor run in period t or not - based on a simulation of 500,000 periods of the model. The regressors are lagged annual growth rates for credit and output. Book value loans are computed using definition (18).*

*Notation: *** Significant at 1 percent, ** Significant at 5 percent, * Significant at 10 percent.*

A.9 Leverage - Data and Definitions

A.9.1 Book vs. Market Leverage

The literature frequently reports leverage ratios of financial institutions which are obtained using only book value data. However, such data depends on specific accounting rules - in particular if and how often financial institutions need to update their balance sheets to current market prices. Hence, measures based on book value data do not correspond to definitions based on market values in economic models. In contrast, market leverage - which can be defined for example as the market value of liabilities divided by the market value of assets - does correspond to the equivalent definitions in economic models. Moreover, it has a simple economic interpretation. The market value of assets, liabilities, or equity is the expected present discounted value of future cash flows to a firm, its creditors, or its shareholders. Market leverage, when defined as $\frac{\text{Market Liabilities}}{\text{Market Assets}}$, gives the (present value) share that belongs to creditors relative to an institution's total future cash flows. In what follows, I describe the data and the assumptions which are made to approximate the market leverage of financial institutions.

A.9.2 Data Description

I largely follow Adrian and Brunnermeier (2011) in the construction of a measure of the financial sector's market leverage, approximated by data on commercial and investment banks. Equity and balance sheet data for commercial banks are collected from the CRSP/Compustat database. Commercial banks are indicated by the SIC Codes 60, 61, and 6712. From CRSP, monthly share prices and number of outstanding shares for commercial banks with these SIC Codes are chosen. From Compustat, quarterly total assets and total liabilities for commercial banks with the mentioned SIC Codes are collected. The quarterly data are converted into monthly data using linear interpolation. The two datasets are merged via the PERMNO identifier. Using the GVKEY identifier, I repeat this exercise for the following selected investment banks: Bear Stearns, Citigroup, Credit Suisse, Goldman Sachs, HSBC, JP Morgan, Lehmann Brothers, Merril Lynch, and Morgan Stanley.

A.9.3 Definitions

Book Leverage. The measure of book leverage in the analysis is based on the following definition

$$Sector\ Book\ Leverage \approx \frac{\sum Book\ Assets_j}{\sum Book\ Assets_j - \sum Book\ Liabilities_j}$$

where the sums are taken over the available observations.

Market Leverage. The market equity of a firm is defined as its share price multiplied by the number of shares outstanding. However, the market leverage of a firm cannot be computed exactly since it requires either data on the market value of assets or the market value of liabilities - both of which are only observed in terms of their book values. In order to approximate the market leverage, one can either assume that

$$Market\ Assets \approx Book\ Assets \tag{78}$$

or

$$Market\ Liabilities \approx Book\ Liabilities \tag{79}$$

and (79) is likely to be a better approximation than (78) due to the shorter maturity of liabilities and hence the more frequent updating on a balance sheet. Given one of these assumptions, the market leverage of institution j is then approximated by

$$Market\ Leverage_j \approx \frac{Book\ Assets_j}{Market\ Equity_j} \tag{80}$$

or

$$Market\ Leverage_j \approx \frac{Market\ Equity_j + Book\ Liabilities_j}{Market\ Equity_j} \tag{81}$$

The financial sector's market leverage is then given by

$$Sector\ Market\ Leverage \approx \frac{\sum Book\ Assets_j}{\sum Market\ Equity_j} \tag{82}$$

or

$$Sector\ Market\ Leverage \approx \frac{\sum Market\ Equity_j + \sum Book\ Liabilities_j}{\sum Market\ Equity_j} \tag{83}$$

where the sums are taken over the remaining observations. For example, at the end of 2010, there are 424 remaining observations in the dataset given definition (82) and 407 given definition (83). The difference in the number of observations is due to the availability of balance sheet data. With respect to the sample which is used for the empirical analysis, the data availability is better with respect to book assets than book liabilities. I therefore primarily work with definition (82) and check robustness using definition (83). All of the results in the chapter are robust to using definition (83) and are available upon request. Figures (31), (32), and (33) plot real book assets, real book liabilities, and real market equity (all in log units) around the Great Recession.

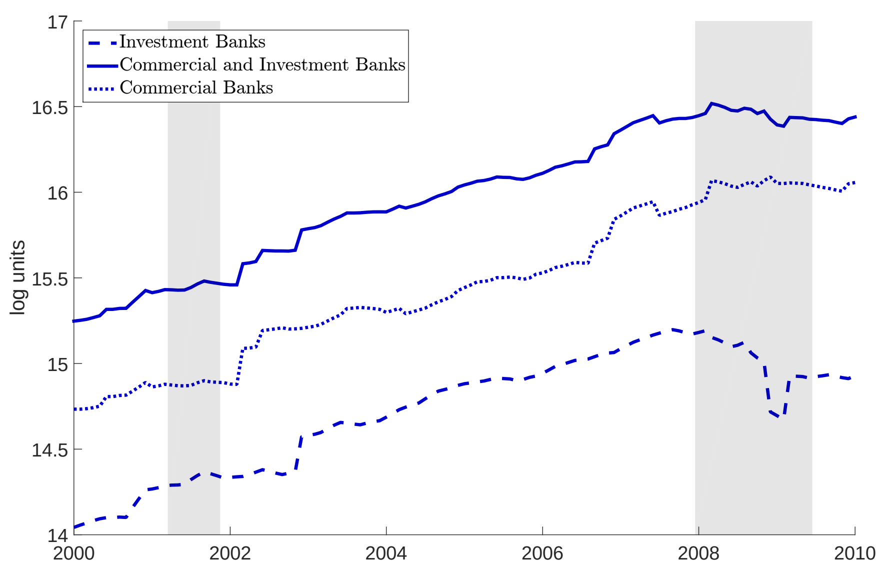


Figure 31: ***Book Assets.*** *The graph shows the evolution of real book assets for different types of U.S. financial institutions around the Great Recession. Grey bars denote NBER recessions.*

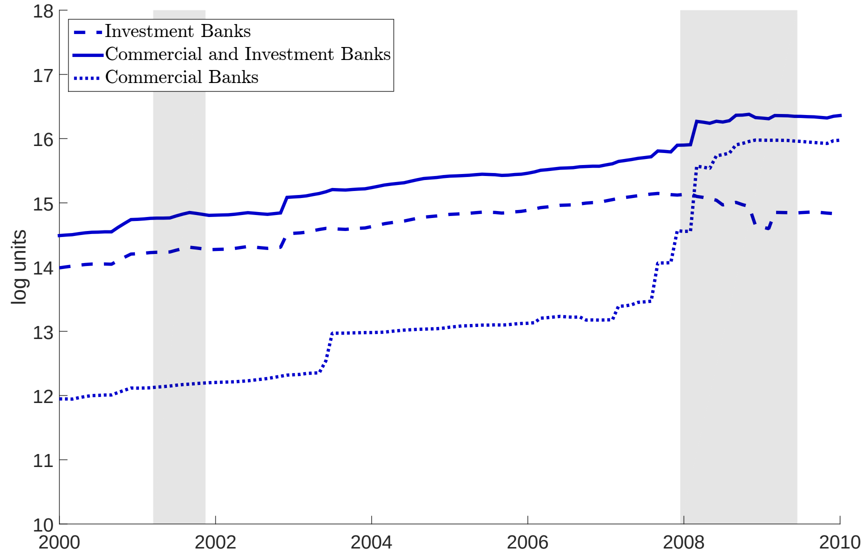


Figure 32: ***Book Liabilities.*** *The graph shows the evolution of book liabilities for different types of U.S. financial institutions around the Great Recession. Grey bars denote NBER recessions.*

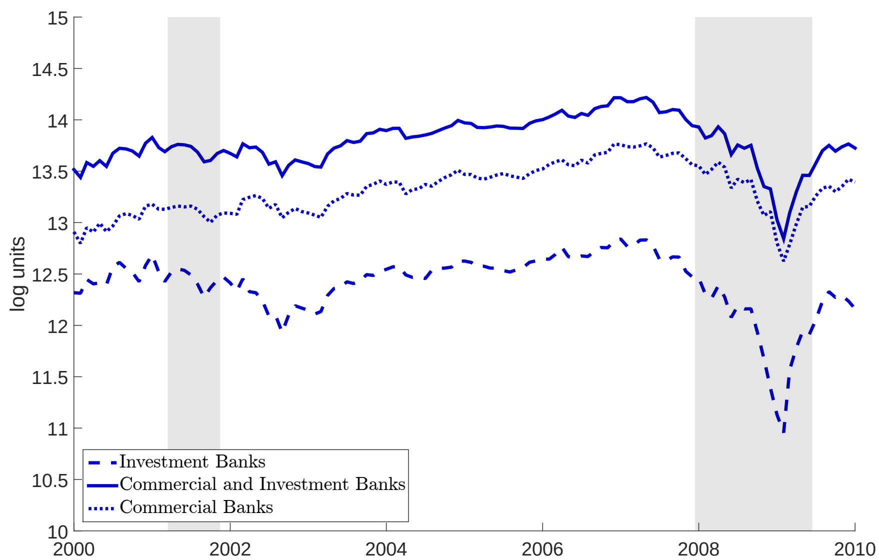


Figure 33: ***Market Equity.*** *The graph shows the evolution of real market equity for different types of U.S. financial institutions around the Great Recession. Grey bars denote NBER recessions.*

B Extension of Chapter I: Nominal Model

This section extends the main model to include price rigidities, nominal debt contracts, and monetary policy. Within this extended version, I analyze the impact of monetary policy on financial stability.

B.1 Monetary Policy

The nominal interest rate is controlled by a monetary authority according to a policy rule of the type suggested by Taylor (1993). Empirical studies find that for several decades prior to the Great Recession the conduct of monetary policy by the U.S. Federal Reserve is well approximated by such a rule (Clarida, Galí and Gertler, 2000), excluding the period highlighted by Taylor (2007) prior to the Great Recession. Monetary policy and price stickiness are introduced as in Gertler and Karadi (2011). The monetary authority controls the nominal interest rate on short-term debt i_t according to

$$i_t = (1 - \rho^m)\left(i^{SS} + \phi_\pi log\Pi_t + \phi_y log\frac{Y_t}{Y_t^*}\right) + \rho^m i_{t-1} + \epsilon_t^m \qquad (84)$$

where i^{SS} is a constant, Π_t is the rate of inflation from period $t-1$ to t, Y_t^* is the natural (flexible price) level of output, and $0 < \rho^m < 1$ reflects the desire of the monetary authority to smooth interest rates. I follow Gertler and Karadi (2011) and use minus the price markup as a proxy for the output gap. In what follows, I turn off the technology shock and the only source of aggregate risk in the model enters via equation (84), where $\epsilon_t^m \sim N(0, \sigma_m^2)$ is a monetary policy shock. The real interest rate is given by the Fischer equation

$$R_t = \frac{(1 + i_{t-1})}{\Pi_t}$$

Debt contracts, both short-term debt between the household and the financial intermediary as well as long-term debt between the financial intermediary and entrepreneurs, are now written in nominal terms. Hence, the real value of debt has to be adjusted for changes in the rate of inflation. In order to keep the description brief, I do not outline the model again, but state the modified model equations in Appendix A.2. Following Gertler and Karadi (2011) and Woodford (2003), I consider the limit of the economy as it becomes cashless.

B.2 Sticky Prices

Another step in the production process is introduced to include price stickiness. The output produced by the good producer via equation (1) is now termed an intermediate good and denoted Y_t^m. Before the intermediate good is used as a consumption good or for conversion into capital goods, it is repackaged and reassembled. Retailers purchase and repackage the intermediate good and sell their output to a final good producer who assembles the retailers' output and sells the final good Y_t. During this process, retailers are subject to price rigidities which follow a similar specification as in Christiano, Eichenbaum and Evans (2005). The final output good Y_t is a CES-composite of a continuum of mass unity of differentiated retail firms' output

$$Y_t = \left(\int_0^1 Y_{j,t}^{\frac{(\epsilon-1)}{\epsilon}} dj \right)^{\frac{\epsilon}{(\epsilon-1)}} \tag{85}$$

where $Y_{j,t}$ is the produced output of retailer j. The final output producer minimizes its costs

$$\min_{Y_{j,t}} P_t Y_t - \int_0^1 P_{j,t} Y_{j,t} dj$$

subject to equation (85). The minimization problem yields the following demand function for retail goods

$$Y_{j,t} = \left(\frac{P_{j,t}}{P_t} \right)^{-\epsilon} Y_t \tag{86}$$

A fraction θ of retailers cannot adjust their price every period. Firms that are allowed to adjust, choose their optimal price P_t^* solving the following problem

$$\max_{P_t^*} \quad \mathbb{E}\left[\sum_{i=0}^{\infty} \theta^i \Lambda_{t,t+i} \left\{ \frac{P_t^*}{P_{t+i}} - P_{t+i}^m \right\} Y_{j,t+i} \right]$$

subject to equation (86). P_t is the price level and P_t^m the intermediate good price in period t. The first-order condition to this problem can be written in recursive form, using the two auxiliary 'forward-looking' variables F_t and Z_t as stated in Appendix A.2. In comparison to the real model, the nominal version has an additional state variable, i.e. last period's price dispersion Δ_{t-1}.

B.3 Calibration

The calibration is adjusted in order to achieve the same targets as in Table (2).[54] The parameters in addition to the real model are summarized in Table (34). Most of the parameters are standard and not further discussed. The probability of price adjustments is calibrated to an average price frequency of 14.5 months, as documented in Kehoe and Midrigan (2014) based on micro-price data and excluding temporary price changes.

Description	***Parameter***	***Value***	***Target / Source***
Price stickiness	θ	*0.793*	*Kehoe and Midrigan (2014)*
Elasticity of substitution	ϵ	*4*	Literature
Inflation coefficient Taylor rule	ϕ_π	*1.5*	Literature
Output gap coefficient Taylor rule	ϕ_y	*0.125*	Literature
Smoothing parameter Taylor rule	ρ_m	*0.8*	Literature
Constant term in Taylor rule	i^{SS}	$\frac{1}{\beta^H} - 1$	Literature
Std. Monetary policy shock	σ_m	*0.29%*	*One-quarter ahead FFR-Futures*

Figure 34: ***Calibration.*** *Calibration of additional structural parameters.*

The calibration of a new parameter which deserves motivation is the standard deviation of the monetary policy shock σ_m. Stating the obvious, this shock comes as a surprise to the economy with respect to the information set one period in advance. A calibration of the standard deviation of this surprise therefore requires a proxy for the economy's expectation about the nominal interest rate and hence the monetary policy's reaction function one quarter in advance. Federal Funds future contracts allow to derive such a proxy. Using 30-day Federal Funds futures from January 1989 until December 2007, I derive a time series of the economy's

[54] The only parameters which are re-calibrated are $\kappa = 0.51$ and $\chi = 1.06$.

expected Federal Funds rate one quarter ahead. Appendix B.7 describes the data in more detail and states calculations. The difference between the expected and the realized Federal Funds rate then gives an estimate for the monetary policy surprises and σ_m is calibrated to the standard deviation of this surprise series, giving $\sigma_m = 0.29\%$. This calibration approach has the advantage that it does not depend on a specific policy rule for the entire sample, but instead allows for changes in the policy rule over time, as long as the market changed its expectations accordingly.

Again, I obtain empirical evidence on the response of the model's main indicator of financial stability (market leverage) to the model's aggregate source of risk (the monetary policy shock). A suitable monetary policy identification technique in this respect is a recent approach by Gertler and Karadi (2015). The main idea of this approach is to combine the high-frequency monetary policy identification with a vector-autoregressive (VAR) model and use surprises obtained from Federal Funds future contracts as external instruments within a VAR. This technique has three advantages: (i) monetary policy shocks are unanticipated, (ii) no timing restrictions are imposed, and (iii) one can trace out the response of variables at longer horizons (while allowing them to interact with other variables in the VAR). I estimate a reduced-form VAR(p)-model

$$X_t = A_0 + \sum_{j=1}^{p} A_j X_{t-j} + u_t \tag{87}$$

where A_0 is a vector of constants, $A_k \; \forall \; k \geq 1$ are coefficient matrices, and the vector X_t comprises the Federal Funds rate (F), the (log) consumer price index, (log) real industrial production, and the market leverage of financial intermediaries.[55] The structural form of the VAR(p)-model can be obtained by pre-multiplying (87) by S^{-1} and the reduced-form errors u_t are related to the structural shocks ϵ_t via $u_t = S\epsilon_t$. Structural shocks are assumed to have a unit variance and the variance-covariance matrix of the reduced form errors is denoted

$$\sum = E\left[u_t u_t'\right] = E\left[SS'\right] \tag{88}$$

[55] Again, data on commercial and investment banks is used (see Appendix A.9 for details).

In order to identify the column s in matrix S which relates each element in u_t to the structural monetary policy shock denoted ϵ_t^F, an external instrument series Z_t is used. In this regard, a series of surprise changes in the contemporaneous month's Federal Funds rate is obtained. This series is derived using Federal Funds future contracts. As for the calibration of σ_m, these future contracts allow to obtain a proxy for the market's expectation of changes in the Federal Funds rate. A surprise change can then be derived by comparing the settlement price of a future contract shortly before and after an FOMC meeting.[56] The conditions for a valid instrument are that the instrument is correlated with the structural shock which relates to the Federal Funds rate, but uncorrelated with all the other structural shocks, i.e.

$$\begin{aligned} E\left[Z_t \epsilon_t^F\right] &= \phi \\ E\left[Z_t \epsilon_t^q\right] &= 0 \end{aligned}$$

where $q \neq F$ and one can argue that both conditions are satisfied for this external instrument series. Further, denote $s^q \in s$ to be the response of u_t^q to a unit-increase in ϵ_t^F as well as $s^F \in s$ to be the response of u_t^F to a unit-increase in ϵ_t^F. The identification of the ratio $\frac{s^q}{s^F}$ then proceeds in two stages. First, u_t^F is projected on Z_t and the fitted values $\hat{u}_t^F$ from this regression are obtained which isolate the variation in u_t^F which is due to the structural shock ϵ_t^F. Second, u_t^q is projected on $\hat{u}_t^F$

$$u_t^q = \frac{s^q}{s^F} \hat{u}_t^F + e_t$$

giving a consistent estimate of the ratio $\frac{s^q}{s^F}$ under the instrument conditions. The ratio $\frac{s^q}{s^F}$ can then be entangled with the help of the variance-covariance matrix of the reduced-form errors, and one can obtain consistent estimates of s^q, s^F, and hence s (see Appendix B.8 for details). Given the vector s, one is able to compute the impulse responses of X_t with respect to the structural shock ϵ_t^F.

[56] Surprises in the current month's Federal Funds rate are used as an instrument series which is derived using a 30-minute window around FOMC meetings. If multiple meetings occur within one month, I derive the combined shock for that month by taking the sum across the individual meetings. In this regard, I thank Peter Karadi and Mark Gertler for sharing their data, which is based on Gürkaynak, Sack and Swanson (2005).

Monthly data from 1979M7 to 2007M12 is used and a VAR-model for $p = 12$ is estimated.[57,58] Figures (35) and (36) plot impulse response functions to a 100 basis points contractionary monetary surprise, using surprises around scheduled and unscheduled FOMC meetings (Figure 35) and surprises around scheduled FOMC meetings only (Figure 36).[59] The latter addresses the concern that the surprise series and therefore the responses are reflecting the release of private information by the Federal Reserve which is particularly a problem around unscheduled FOMC meetings.[60] The instrument series used for Figure (36) therefore excludes surprises around unscheduled FOMC meetings. Following a contractionary monetary policy surprise, the Federal Funds Rate increases, while industrial production and the consumer price index decrease - given a price puzzle. Importantly, market leverage increases in the short run for both instrument series and crosses the x-axis after around 10 months or 3-4 quarters (in Figure 36). Hence, financial intermediaries are subject to short-term interest rate risk and an unanticipated increase in the short-term interest rate pressures their balance sheet and leads to an increase in their market leverage in the short run.[61]

[57] The choice for starting point of the sample follows the reasoning in Gertler and Karadi (2015) and coincides with the beginning of Paul Volcker's tenure as Federal Reserve chair. The end point is chosen to exclude the Great Recession. A timing issue arises since the external instrument series Z_t is available for a shorter time span (1989-2007) than the time frame on which the VAR is estimated (1979-2007). Following Gertler and Karadi (2015), the VAR is first estimated on the longer sample, the reduced form errors from this estimation are restricted to the shorter sample, and then used to identify the vector s.

[58] The lag length of the VAR is chosen as suggested by the Hannah-Quinn information criterion.

[59] Confidence bands are computed via a wild bootstrap as in Mertens and Ravn (2013) and Gertler and Karadi (2015). This bootstrapping procedure has the advantage that generated regressor problems are avoided as the step associated with the identification via the instrument is included in the bootstrapping procedure, leading to valid confidence bands under heteroscedasticity and strong instruments. 10,000 bootstrap repetitions are used to obtain the impulse responses.

[60] The F-statistic and the robust F-statistic from the first stage of the identification are well above the threshold of 10, when using surprises around scheduled and unscheduled FOMC meetings, as suggested by Stock, Wright and Yogo (2002). However, when using the instrument series comprising surprises around scheduled FOMC meetings only, these values drop below 10 and therefore problems associated with weak instruments cannot be excluded.

[61] In separate VAR-specifications, I confirm that the initial increase in market leverage is due to an immediate decrease of the market equity of financial institutions following a contractionary monetary policy surprise, while book values are responding more slowly. These additional results are in line with the impulse responses presented in section B.4 and are available upon request.

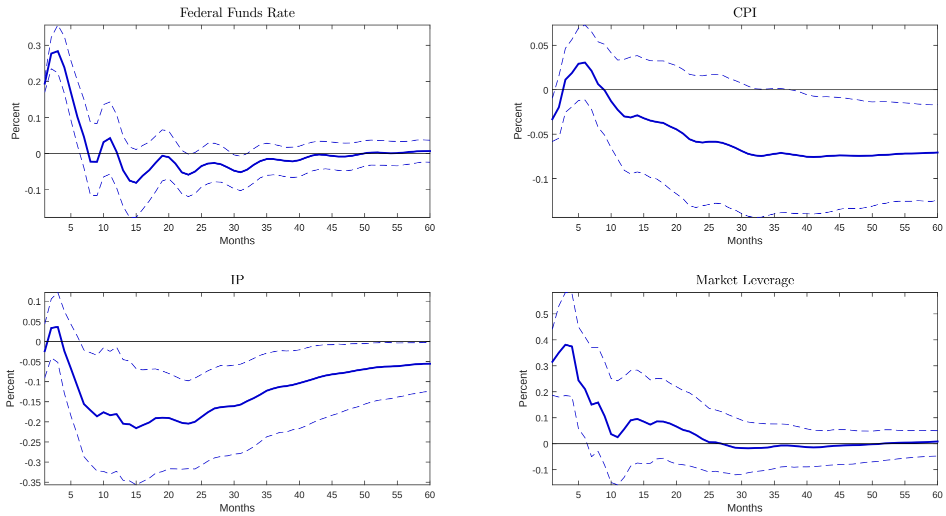


Figure 35: ***Impulse Response Functions.*** *IRF to a 100 basis points contractionary monetary policy surprise. Sample: 1979M1-2007M12. Instrument series: Surprises around scheduled and unscheduled FOMC meetings obtained from future contracts with respect to the current month's Federal Funds Rate. First-stage regression: F-stat: 25.15. Robust F-stat: 25.82. 95% confidence bands are shown.*

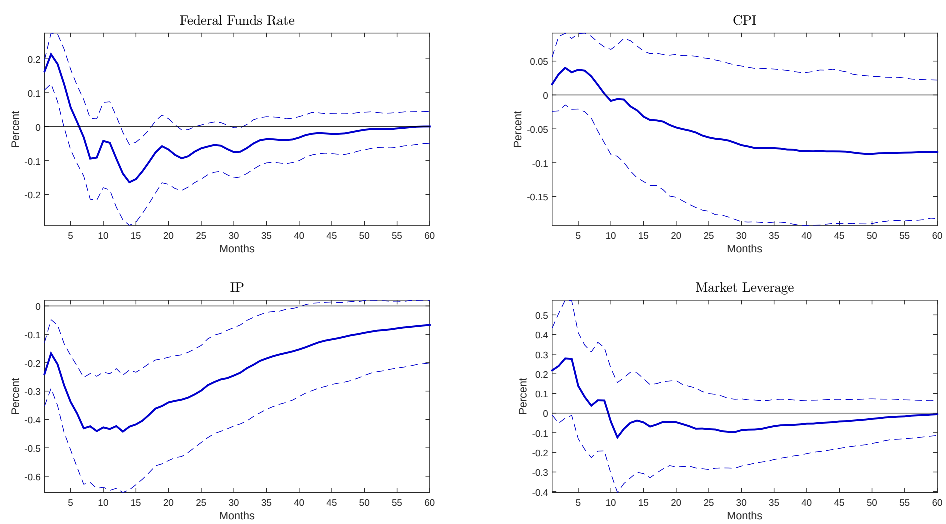


Figure 36: ***Impulse Response Functions.*** *IRF to a 100 basis points contractionary monetary policy surprise. Sample: 1979M1-2007M12. Instrument series: Surprises around scheduled FOMC meetings obtained from future contracts with respect to the current month's Federal Funds Rate. First-stage regression: F-stat: 5.35. Robust F-stat: 3.89. 95% confidence bands are shown.*

Again, given β^H, I calibrate β^F to match the initial sign and turning-point of the empirical impulse response, i.e. an initial increase followed by a decrease after 3-4 quarters. Again, this calibration approach gives an asset-to-equity ratio of around 2.

B.4 Impulse Response Functions

Figures (37) and (38) show impulse response functions to a one standard deviation contractionary monetary policy shock, starting from the stochastic steady state of the model. Output Y_t, consumption C_t, hours H_t, and inflation Π_t decrease. When analyzing the dynamics for entrepreneurs, one can differentiate between outstanding and new loans. Since the real profits on capital $R_t^K Q_{t-1}^K$ decrease and the real burden of outstanding debt increases due to lower inflation, default probabilities on entrepreneurs' loans, which were given out prior to the shock, increase. To illustrate this point, Figure (38) shows the evolution of the default threshold for the vintage of loans given out one period prior to the contractionary monetary policy shock $\overline{\omega}_{t|0} = \frac{L_0^{new}}{R_t^K Q_{t-1}^K K_0^{new} \prod_{k=1}^{t} (\Pi_k)}$, where zero indicates the period prior to the shock. However, lower profits for entrepreneurs also intensify the risk-shifting problem. The real amount of credit issued to new entrepreneurs $Q_t L_t^{new}$ is rationed in order to ensure that they invest into the good project and the loan-to-capital ratio on newly issued loans $\frac{L_t^{new}}{K_t^{new}}$ declines. Due to the contraction in lending, the economy's capital stock K_t decreases. In contrast to outstanding loans, newly issued loans show an initial decline in default probabilities, as highlighted by the evolution of the default threshold for the vintage of loans given out in the period when the shock realizes $\overline{\omega}_{t|1} = \frac{L_1^{new}}{R_t^K Q_{t-1}^K K_1^{new} \prod_{k=2}^{t} (\Pi_k)}$. The model therefore confirms the asymmetric response in default probabilities on new vs. outstanding loans, as shown empirically by Jiménez et al. (2009, 2014).

When analyzing the intermediary's balance sheet, it is again important to take into account how inflation changes the real value of nominal contracts, since both the intermediary's liabilities and assets are denoted in nominal terms. To illustrate the impact of inflation, the responses of debt B_t and loans L_t are shown both in real and nominal terms. After a

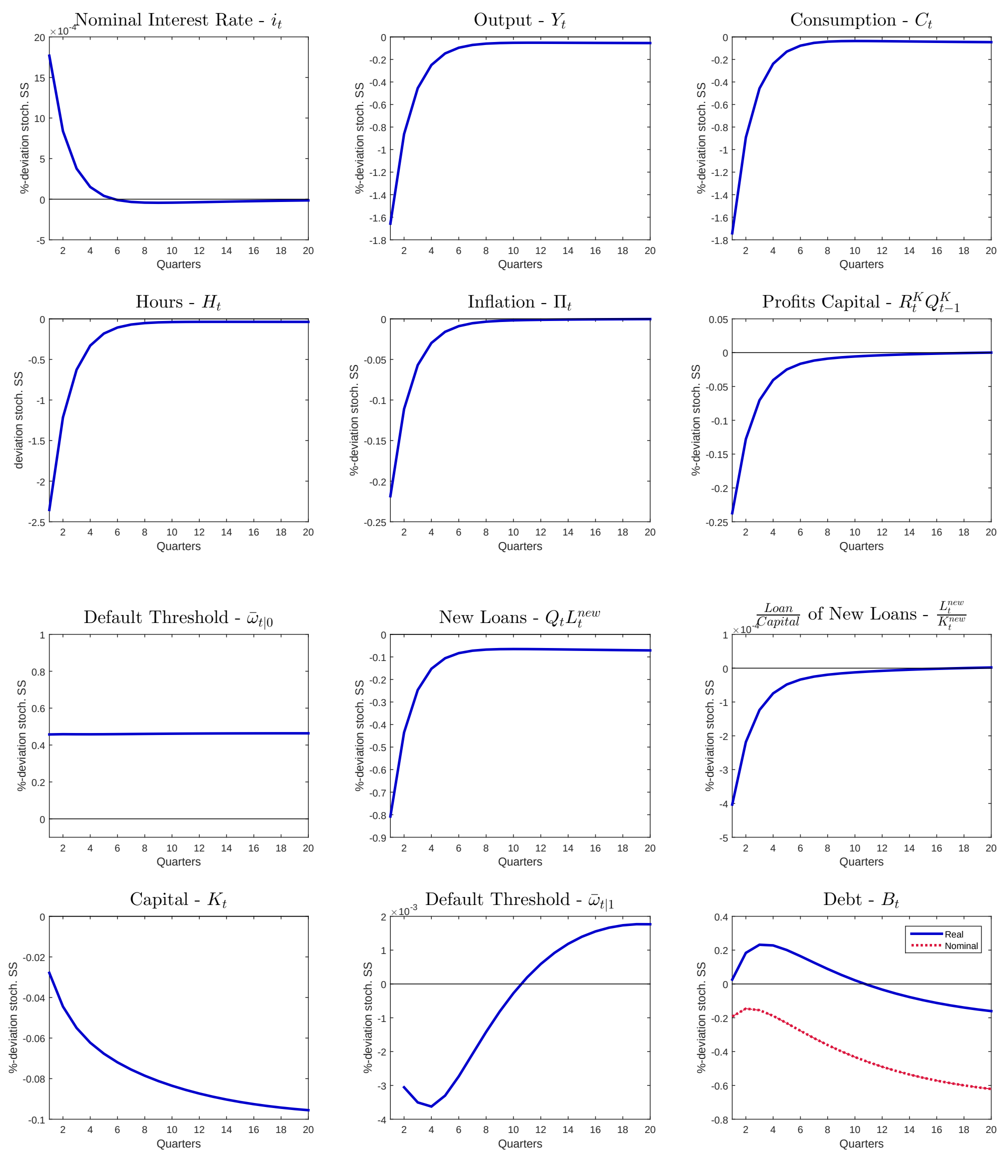


Figure 37: ***Impulse Response Functions.*** *IRFs to a one standard deviation contractionary monetary policy shock, starting at stochastic steady state of the model.*

contractionary monetary policy shock, the nominal interest rate increases and the intermediary reduces its nominal debt, given this price increase. However, due to the decrease in inflation, the real value of debt B_t actually increases.

On the asset side, the financial intermediary faces a decline in the profits of its portfolio of real loans $R_t^L Q_{t-1}$ due to the increase in default thresholds on outstanding loans. However, if a loan does not default, the real value of repayment actually increases due to lower inflation. Even though the issuance of new loans $Q_t L_t^{new}$ contracts, the stock of outstanding loans L_t increases in real terms, which is again due to lower inflation. Since the real value of outstanding loans increases, loan-to-capital ratios on outstanding loans rise as well. The loan risk indicator x_t therefore increases, even though new loans are issued with lower loan-to-capital ratios $\frac{L_t^{new}}{K_t^{new}}$.

Given these countervailing effects, the intermediary initially reduces the amount of dividends paid out to shareholders D_t, since the decline in the intermediary's profits, the increased cost of funding, and the rise in the real value of the intermediary's debt dominate. Leverage $\frac{B_t}{Q_t L_t}$ initially increases, because the whole portfolio of loans drops in value. Over time, the price of loans Q_t returns and the intermediary reduces its real debt burden, leading to a decrease in the intermediary's leverage over time. The path of leverage therefore roughly matches the empirical evidence shown above - an initial increase with a decrease after around four quarters. However, the following decline in leverage is more persistent than in the data which is due to the model's inherent persistence coming from the stochastic maturity set-up.

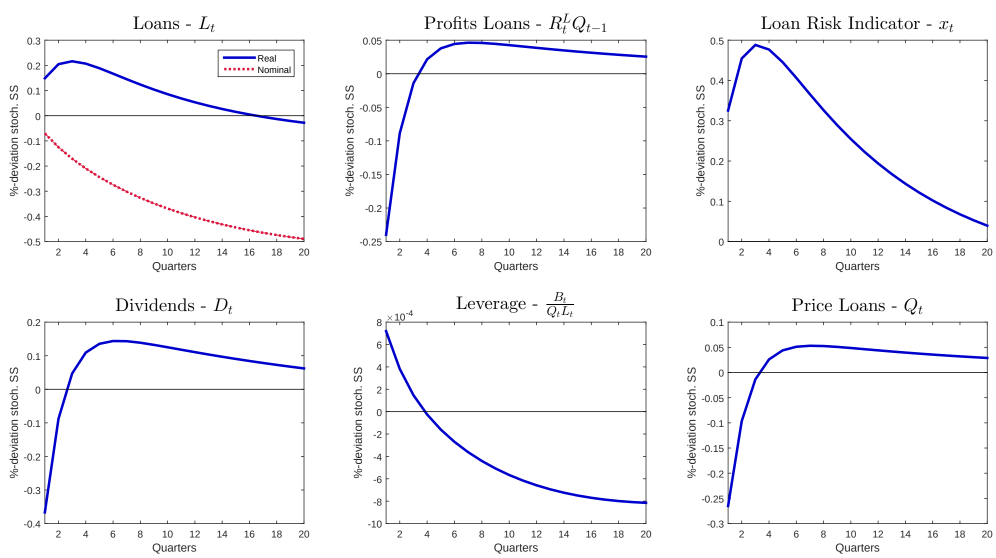


Figure 38: ***Impulse Response Functions.*** *IRFs to a one standard deviation contractionary monetary policy shock, starting at stochastic steady state of the model.*

B.5 Financial Crises

The analysis in section 4.9 is repeated for the nominal model. Figures (39) and (40) show the typical behavior of the nominal economy around financial crises. The first row in Figure (40) plots the behavior of the monetary policy shock ϵ_t^m and the nominal interest rate i_t. A typical build-up period leading to a financial crisis is characterized by a longer period of expansionary monetary policy and at the end of this period the probability that a crisis will occur in the next quarter has already strongly risen. A crisis is initiated by a few contractionary monetary policy shocks. The nominal interest rate therefore steadily declines in the run-up and then increases. Hence, both expansionary and contractionary monetary policy can increase financial instability and it is a U-shaped pattern of the policy target rate which is particularly likely to adversely affect financial stability (see below for a discussion in this regard). As in the real model, financial crises occur out of boom periods and are initiated by moderate adverse changes in the nominal interest rate. The median shock which triggers a crisis is a 1.19 standard deviation positive monetary policy shock.

Output Y_t, capital K_t, hours H_t, and inflation Π_t all increase in the build-up period and then sharply decrease. The rise and fall of inflation Π_t influences the dynamics of the intermediary's balance sheet. In order to isolate the impact of inflation, debt B_t and loans L_t are again shown in real and nominal terms.[62] In nominal terms, the intermediary strongly expands its balance sheet - taking on more debt to issue more loans since incentives to risk-shift decrease in good times and the agency problem is relaxed. However, due to the rise of inflation in the boom, the real amount of outstanding loans is constantly adjusted downwards. The total amount of loans L_t in real terms therefore remains fairly constant in the boom, even though more loans $Q_t L_t^{new}$ are issued. Inflation also lowers the real burden of debt B_t, but because the expansion in nominal terms overweighs, the real amount of debt slightly increases in the boom. And since the real price of loans Q_t remains fairly constant, the intermediary's leverage $\frac{B_t}{Q_t L_t}$ increases in the boom.

[62] In order to convert real into nominal series, a time series of the price level is obtained, the log of this series is linearly detrended, and then used to convert real into nominal series.

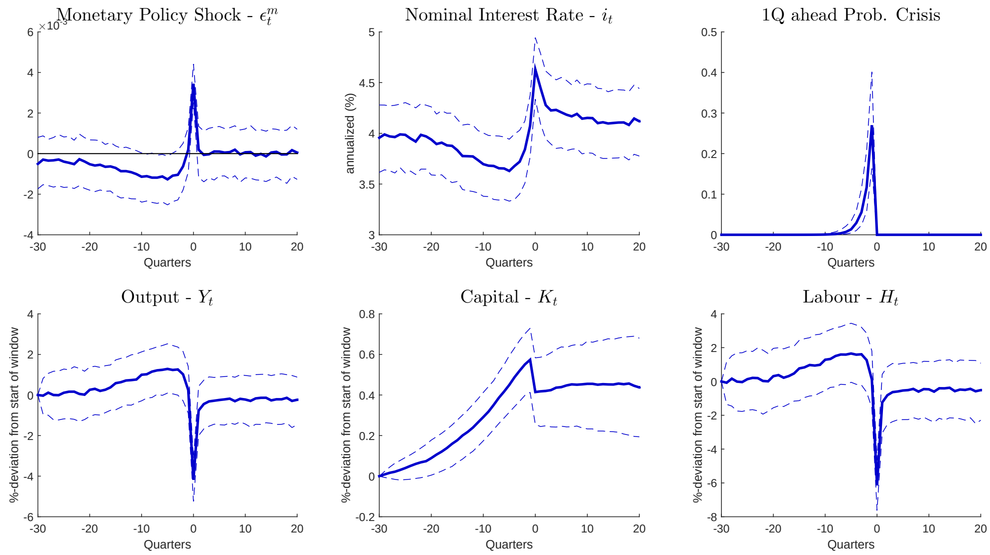


Figure 39: ***Typical Financial Crises.*** *Event window around financial crisis at Quarter = 0. Based on a simulation of 500,000 periods. Median, 33rd, and 66th percentiles are shown.*

In contrast to the real model, the loan risk indicator x_t slightly decreases in the boom, since loan-to-capital ratios of outstanding loans fall and the rise of loan-to-capital ratios on newly issued loans $\frac{L_t^{new}}{K_t^{new}}$ cannot overturn this effect. However, in contrast to the real model, x_t sharply rises in the bust, since the rate of inflation Π_t drops and loan-to-capital ratios on outstanding loans increase. The weighted default threshold $\overline{\omega}_t$ behaves in a similar way. Compared to the real model, $\overline{\omega}_t$ increases more strongly in the bust due to the change in inflation which raises default thresholds in addition to the fall in profits on capital.

In contrast to the real model, the rise in the value of loans Q_t, the intermediary's profits $R_t^L Q_{t-1}$, and dividends D_t is less pronounced in the nominal model due to the changes in inflation and the readjustment of real loans. As in the real model, the behavior of leverage is consistent with the data as shown in Figure (1), and expected excess returns $\mathbb{E}\left[R_{t+1}^X\right]$ spike because of the liquidity-premium.

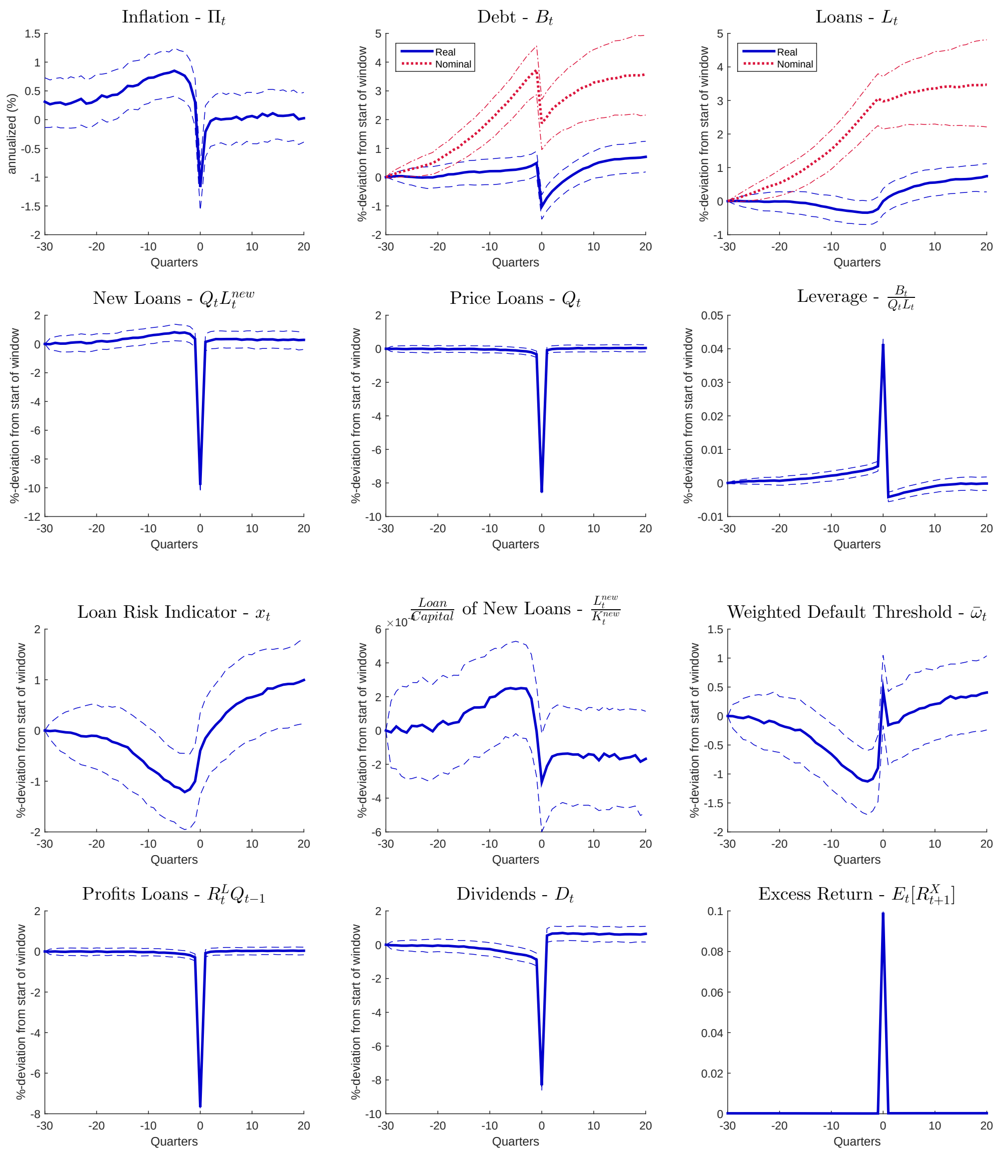


Figure 40: ***Typical Financial Crises.*** *Event window around financial crisis at Quarter = 0. Based on a simulation of 500,000 periods. Median, 33rd, and 66th percentiles are shown.*

B.6 Monetary Policy & Financial Stability

The model predicts that a U-shaped pattern of monetary policy is particularly likely to increase financial instability. The behavior of the nominal interest rate therefore takes a similar shape as the counterparts in the U.S. before the Great Recession and in Japan in the late 1980s/early 1990s as shown in Figure (41). However, the increases in the nominal interest rate which initiate a financial crisis in the model are much larger than the step-by-step increases in the nominal interest rates as seen in Figure (41). The model therefore offers a reason why central banks raise nominal interest rates in small steps. Small steps avoid to put too much pressure on the balance sheets of financial institutions.

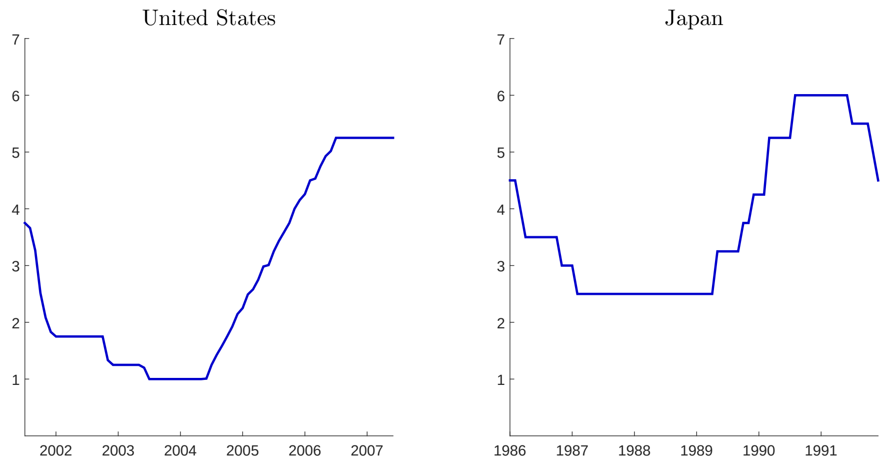


Figure 41: ***Monetary Policy.*** *Left: U.S. Monetary Policy, Federal Funds Target Rate. Right: Japanese Monetary Policy, Discount rate. Source: Fred Database Federal Reserve Bank of St. Louis.*

However, while small increases in the target rate may not be able to cause a crisis, they still put additional pressure on financial intermediaries' balance sheets. The model therefore highlights the dilemma of central banks when trying to "lean against the wind" using monetary policy. In the short run, contractionary monetary policy may increase financial instability instead of decreasing it. A trade-off between price and financial stability may therefore arise during boom periods, when rising prices are pressuring the economy and increases in the target rate can work against such price pressures, but may also increase financial instability in the short run. Moreover, since periods of low interest rates intensify the adverse impact of contractionary monetary policy on financial stability, they should be avoided by central banks if financial stability concerns outweigh other motives.

B.7 Monetary Policy Surprises

30-day Federal Funds future contracts are used to obtain a series of the economy's expectation about future nominal interest rates. These contracts are traded at the Chicago Mercantile Exchange and historical pricing series are obtained. The timing and pricing of these contracts works as follows. A 30-day Federal Funds Future contract traded in month $k - x$ for $x \geq 0$ is a bet on the average Federal Funds rate for month k. Given the price in month $k - x$, the expected Federal Funds rate in month $k - x$ for the Federal Funds rate in month k can be obtained via

$$E_{k-x}\left[mean\left(FFR_k\right)\right] = 100 - Price_{k-x}$$

for $x \geq 1$. The monthly frequency is converted into a quarterly frequency as follows. The price for some month k is derived on the mid-day in the mid-month in the quarter prior to month k. For example, for January, February, and March, the price is obtained on the 15^{th} of November prior to those months. A quarterly series is then obtained by averaging over the related three expected Federal Funds rates. The difference between the derived series of expectations and the quarterly average of the realized Federal Funds rate gives a series of quarterly monetary policy surprises which is used to calibrate the standard deviation of the monetary policy shock.

B.8 Derivation Monetary Policy Identification

The description on how to separate s^F from the ratio $\frac{s^q}{s^F}$ follows footnote 4 in Gertler and Karadi (2015) and is here repeated for completeness. Partition u_t, S, and the reduced form error variance-covariance matrix $\sum = E\left[u_t u_t'\right] = E\left[SS'\right]$ as

$$\begin{aligned} u_t &= \left[u_t^F u_t^{q'}\right]' = \left[u_{1t} u_{2t}^{'}\right]' \\ S &= \left[s\ S_q\right] = \left[S_1\ S_2\right] = \begin{bmatrix} s_{11} & s_{12} \\ s_{21} & s_{22} \end{bmatrix} \\ \sum &= \begin{bmatrix} \sum_{11} & \sum_{12} \\ \sum_{21} & \sum_{22} \end{bmatrix} \end{aligned}$$

s^F is then identified via

$$(s^F)^2 = s_{11}^2 = \sum{}_{11} - s_{12}s_{12}'$$

where

$$s_{12}s_{12}' = \left(\sum{}_{21} - \frac{s_{21}}{s_{11}}\sum{}_{11}\right)' Q^{-1}\left(\sum{}_{21} - \frac{s_{21}}{s_{11}}\sum{}_{11}\right)$$

and

$$Q = \frac{s_{21}}{s_{11}}\sum{}_{11}\frac{s_{21}'}{s_{11}} - \left(\sum{}_{21}\frac{s_{21}'}{s_{11}} + \frac{s_{21}}{s_{11}}\sum{}_{21}^{'}\right) + \sum{}_{22}$$

C Appendix to Chapter II

C.1 Estimation Algorithm

The unknown objects of the model are the history of the volatilities Σ^T, the coefficients B^T, the coefficients A^T, and the variance covariance matrix V. Following Primiceri (2005), Gibbs sampling is used to evaluate the posterior distribution of these unknown objects. Apart from the corrections by Del Negro and Primiceri (2015), I closely follow the algorithm in Appendix A in Primiceri (2005). The steps of the sampler are:

1. Initialize A^T, Σ^T, s^T, and V
2. Sample B^T from $p\left(B^T|y^T, A^T, \Sigma^T, V\right)$
3. Sample s^T from $p\left(s^T|y^T, A^T, B^T, \Sigma^T, V\right)$
4. Sample Σ^T from $p\left(\Sigma^T|y^T, A^T, B^T, s^T, V\right)$
5. Sample V by sampling Q, W, S from $p\left(Q, W, S|y^T, A^T, B^T, \Sigma^T\right)$
6. Repeat step 2.

where $p(\cdot|\cdot)$ denotes a conditional density and s^T is a matrix of mixture indicator variables given the notation in Appendix A in Primiceri (2005), to which the interested reader is referred for further details on the estimation algorithm. For the Ω-Model, the steps reduce to

1. Initialize V
2. Sample B^T from $p\left(B^T|y^T, V\right)$
3. Sample V by sampling Ω and Q from $p\left(\Omega, Q|y^T, B^T\right)$
4. Repeat step 2.

I check parameter convergence via trace plots and autocorrelation functions of the draws. The results show that the estimation algorithm produces posterior draws efficiently.

C.2 Derivation Fundamental Stock Price Response

This section derives the impulse response of the fundamental component of stock prices to a monetary policy shock. The derivation largely follows Cochrane (2001, page 396). Start with an identity and rearrange

$$\begin{aligned} 1 &= \tilde{R}_{t+1}^{-1}\tilde{R}_{t+1} \\ &= \tilde{R}_{t+1}^{-1}\left(\frac{P_{t+1}^F + D_{t+1}}{P_t^F}\right) \\ P_t^F &= \tilde{R}_{t+1}^{-1}\left(1 + \frac{P_{t+1}^F}{D_{t+1}}\right) D_{t+1} \end{aligned}$$

Take logs, indicated by small letters,

$$p_t^F = -\tilde{r}_{t+1} + d_{t+1} + ln\left(1 + e^{p_{t+1}^F - d_{t+1}}\right)$$

Take a Taylor expansion of $ln\left(1 + e^{p_{t+1}^F - d_{t+1}}\right)$ around $\frac{P^F}{D} = e^{p^F - d}$

$$p_t^F = -\tilde{r}_{t+1} + d_{t+1} + ln\left(1 + \frac{P^F}{D}\right) + \frac{\frac{P^F}{D}}{1 + \frac{P^F}{D}}\left(p_{t+1}^F - d_{t+1} - \left(p^F - d\right)\right) \tag{89}$$

In steady state, the price is

$$P^F = D\left(\Lambda + \Lambda^2 + \Lambda^3 + ...\right)$$

where $\Lambda = \frac{\Gamma}{R}$, Γ is the gross real growth rate of dividends, and R is the gross real interest rate. Then, the price-to-dividend ratio is given by

$$\frac{P^F}{D} = \frac{\Lambda}{1 - \Lambda}$$

and equation (89) can be written as

$$p_t^F = -\tilde{r}_{t+1} + d_{t+1} + const. + \Lambda\left(p_{t+1}^F - d_{t+1}\right)$$

Assume that the return $\tilde{r}_{t+1}$ is equal to the real interest rate r_t plus the risk-premium rp_{t+1}. Taking this into account and solving the above equation forward gives

$$p_t^F = const. + \sum_{j=0}^{\infty} \Lambda^j \left[(1-\Lambda)\, d_{t+j+1} - r_{t+j} - rp_{t+j+1} \right]$$

The impulse response of the fundamental component to a monetary policy shock ϵ_t^P is then

$$\frac{\partial p_{t+k}^F}{\partial \epsilon_t^P} = \sum_{j=0}^{\infty} \Lambda^j \left[(1-\Lambda) \frac{\partial d_{t+k+j+1}}{\partial \epsilon_t^P} - \frac{\partial r_{t+k+j}}{\partial \epsilon_t^P} - \frac{\partial rp_{t+k+j+1}}{\partial \epsilon_t^P} \right] \quad for\ k = 0, 1, 2, ...$$

and the response of the fundamental price in the impulse response figures is obtained using this equation and holding the response of risk-premia constant. Λ is set to $\frac{1}{1+\frac{0.04}{12}}$ consistent with monthly data. 250 periods are used to approximate the sum and I find that the results of the time varying parameter VARs are robust to approximating the sum for longer periods. With respect to the constant parameter VARs in section 5.3 (with short-run restrictions) and in Appendix C.4 (without short-run restrictions), I find that stock prices respond mildly less than the implied fundamental at longer horizons for the constant parameter VAR with short-run restrictions, but not for the one without such restrictions, when approximating the sum for very long periods.

C.3 Granger-Causality Tests

	$\mathbb{S}_t$	$\mathbb{S}_t$	$\mathbb{S}_t$	$\mathbb{S}_t$	$\mathbb{S}_t$
$Constant$	$\surd$	$\surd$	$\surd$	$\surd$	$\surd$
y_{t-k}	$k=1$	$k=1,2$	$k=1,..,3$	$k=1,...,4$	$k=1,...,5$
Observations	278	277	276	275	274
F-statistic	1.33	1.33	1.35	1.09	1.21
Prob>F	0.25	0.21	0.17	0.36	0.22

Table 10: *The table shows the results from several regressions for which the dependent variable is the series of monetary policy surprises (current month future contracts, around scheduled meetings) and lagged values of y_t are the regressors. The F-tests show that y_t is not Granger-causing $\mathbb{S}_t$.*

C.4 Monetary Policy Surprises as External Instruments

This section outlines the monetary policy identification approach by Gertler and Karadi (2015) who use monetary policy surprises as external instruments with respect to a VAR. Their method is applied to the data described in section 5.2. Let y_t be a vector of time series comprising the Federal Funds rate, the (log) real stock price index (S&P 500), the associated (log) real dividends, the (log) consumer price index, and (log) real industrial production. This vector is approximated by a VAR(k)-model, estimated for example from an ordinary least squares regression,

$$y_t = B_0 + \sum_{j=1}^{k} B_j y_{t-j} + u_t$$

where B_0 is a vector of constants, B_j for $j \geq 1$ are coefficient matrices, and u_t are reduced-form errors. The structural form of the VAR(p)-model is given by

$$G_0 y_t = G_0 B_0 + \sum_{j=1}^{p} G_j y_{t-j} + \epsilon_t \tag{90}$$

where $G_j \ \forall \ j \geq 0$ are coefficient matrices and ϵ_t are structural white noise shocks. The reduced and the structural representation are linked via

$$\begin{aligned} G_j &= G_0 B_j \\ u_t &= S\epsilon_t \end{aligned}$$

where $S = G_0^{-1}$ and the structural shocks are assumed to have a unit variance such that the reduced-form error variance-covariance matrix is $\sum = E\left[u_t u_t'\right] = E\left[SS'\right]$. Let $y_t^p \in y_t$ be the Federal Funds rate with the associated structural shock ϵ_t^p and reduced form error u_t^p. Denote by ϵ_t^q the structural shock and by u_t^q the reduced form error related to variable $q \neq p$. The interest lies in the response of the variables collected in y_t to an exogenous variation in ϵ_t^p which is uncorrelated with all ϵ_t^q. In order to recover such a variation, external instruments

z_t are used. The conditions for z_t to be valid instruments are that they are correlated with ϵ_t^p, but not with any ϵ_t^q

$$\begin{aligned} E[z_t \epsilon_t^p] &= \phi \\ E[z_t \epsilon_t^q] &= 0 \end{aligned}$$

Given a set of valid instruments, the identification proceeds as follows. Denote by s the column in S which relates the reduced form shocks to ϵ_t^p. Further, let $s^p \in s$ be the response of u_t^p to a unit change in ϵ_t^p and $s^q \in s$ the response of u_t^q to a unit change in ϵ_t^p. In order to identify s, a two-step approach is applied.

1. Project u_t^p on z_t and obtain the fitted values $\hat{u}_t^p$ which capture the variation in u_t^p which is due to ϵ_t^p.

2. Project u_t^q on $\hat{u}_t^p$. The estimated coefficient in the second step gives a consistent estimate of $\frac{s^q}{s^p}$ under the instrument conditions.

With the help of the variance covariance matrix of the reduced-form errors, one is then able to recover s^q, s^p, and hence s.[63] Given the vector s, the impulse responses of y_t with respect

[63]The description on how to separate s^p from the ratio $\frac{s^q}{s^p}$ follows footnote 4 in Gertler and Karadi (2015) and is here repeated for completeness. Partition u_t, S, and the reduced form error variance-covariance matrix $\sum = E\left[u_t u_t'\right]$ as

$$\begin{aligned} u_t &= \left[u_t^p u_t^{q'}\right]' = \left[u_{1t} u_{2t}'\right]' \\ S &= [s\ S_q] = [S_1\ S_2] = \begin{bmatrix} s_{11} & s_{12} \\ s_{21} & s_{22} \end{bmatrix} \\ \sum &= \begin{bmatrix} \sum_{11} & \sum_{12} \\ \sum_{21} & \sum_{22} \end{bmatrix} \end{aligned}$$

s^p is then identified via

$$(s^p)^2 = s_{11}^2 = \sum{}_{11} - s_{12}s_{12}'$$

where

$$s_{12}s_{12}' = (\sum{}_{21} - \frac{s_{21}}{s_{11}} \sum{}_{11})' Q^{-1} (\sum{}_{21} - \frac{s_{21}}{s_{11}} \sum{}_{11})$$

and

$$Q = \frac{s_{21}}{s_{11}} \sum{}_{11} \frac{s_{21}'}{s_{11}} - (\sum{}_{21} \frac{s_{21}'}{s_{11}} + \frac{s_{21}}{s_{11}} \sum{}_{21}') + \sum{}_{22}$$

to the structural shock ϵ_t^p can be computed. The outlined identification approach is applied to the same sample period as in section 5.3 and in accordance with this section, monetary policy surprises obtained from the current month's Federal Funds future around scheduled FOMC meetings are used as the external instrument z_t. Figure (42) shows the impulse responses to a 100 basis point contractionary monetary policy surprise.[64]

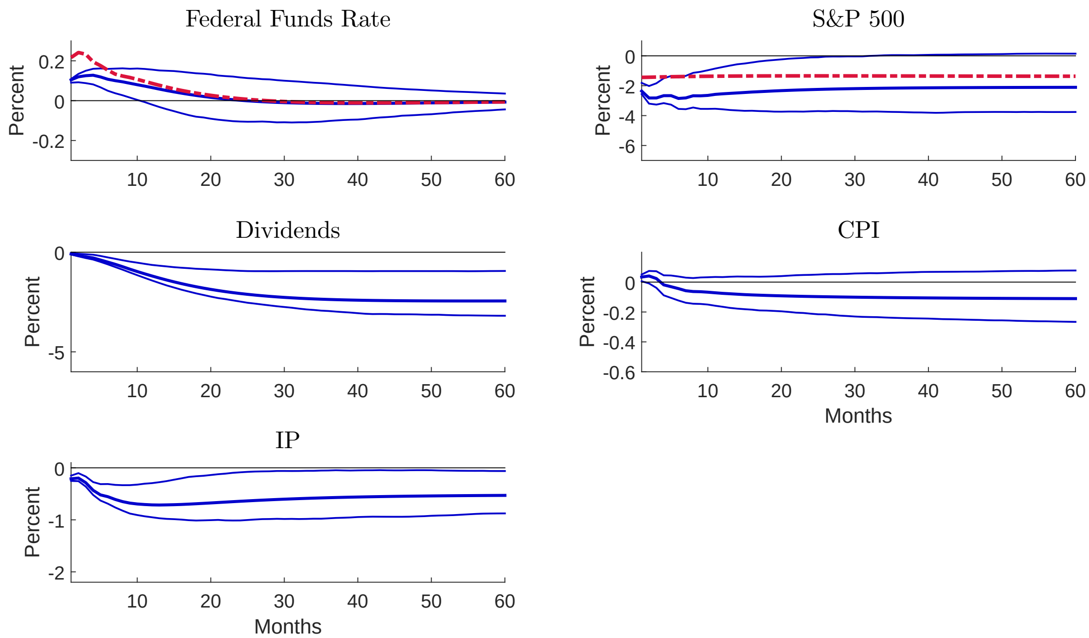


Figure 42: ***Impulse Response Functions - External Instrument Approach.*** *IRFs to a 100 basis point surprise contractionary monetary policy shock. 95% confidence bands are shown. The red dotted line in the plot of the Federal Funds rate is the real interest rate. The red dotted line in the plot of the S&P 500 shows the response of the stock price based on discounted dividends (see Appendix C.2). F-statistic: 13.18. Robust F-statistic: 8.32 with respect to the first stage regression.*

These responses should be compared to figure (43) which shows the IRFs for the constant parameter VAR based on the exogenous variable approach in this chapter and without short-run restrictions, such that the consumer price index and industrial production can react contemporaneously to a monetary policy surprise.[65] The size of the shock is normalized to match the initial increase in the Federal Funds rate as given by Gertler & Karadi's identification. The

[64]The lag length is set to $k = 4$ for the two VARs as suggested by Akaike's information criterion.
[65]The lag length is set to $k = 4$ for the two VARs as suggested by Akaike's information criterion.

obtained impulse responses in figure (42) and (43) are nearly equivalent, but the confidence bands are wider for the exogenous variable approach.

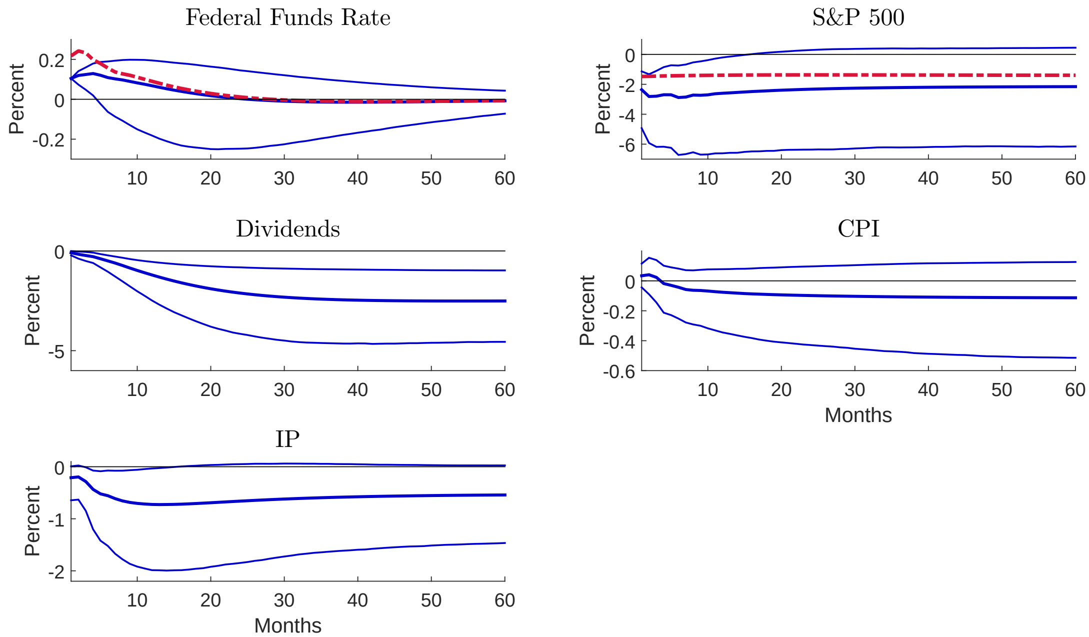


Figure 43: ***Impulse Response Functions - Exogenous Variable Approach - No Short-Run Restrictions.*** *IRFs to a contractionary monetary policy surprise, normalized to to give the same initial increase in the Federal Funds rate as obtained with external instrument approach. 95% confidence bands are shown. The red dotted line in the plot of the Federal Funds rate shows the real interest rate. The red dotted line in the plot of the S&P 500 shows the response of stock prices based on discounted dividends and constant risk-premia (see Appendix C.2).*

Two comments are in order to explain these findings. First, the ratio $\frac{s^q}{s^p}$ obtained using the "external instrument approach" is exactly the same as the equivalent estimated ratio based on the coefficient vector B_{k+1} in model (19) with constant parameters. Hence, the contemporaneous relation between the endogenous variables and the surprises is the same using the two approaches (up to a normalization of the shock). However, the coefficients to the constant and to lagged endogenous variables are affected by the inclusion of z_t into the VAR and the subsequent impulse responses therefore slightly change, when the shock propagates through the system (however, this difference is almost invisible to the naked eye). Second, the confidence bands are wider using the exogenous variable approach, even though the same bootstrapping method is used for the approaches (a "wild bootstrap" as in Mertens and Ravn (2013) and Gertler and Karadi (2015) is applied). The reason for this result is that z_t partly explains the data and the bootstrapping method takes this into account when distorting the residuals from the VAR, which includes the surprises, in order to construct new time series for y_t which are used to re-estimate the VAR. In contrast, using the external instrument approach the distorted residuals are constructed without taking this relation into account which results in tighter confidence bands.

A difference between the method in this chapter and the external instrument approach is the following. Gertler and Karadi (2015) estimate their VAR first on a longer sample than their monetary policy surprise series is available, restrict the residuals from this estimation to the sample period for which the monetary policy surprise series is available, and then proceed with the external steps for the smaller sample. In contrast, the method in this chapter requires all time series to be continuously available. I make use of the step-wise approach by Gertler and Karadi (2015) and estimate the VAR for the sample 1960M1-2011M12 which is the one considered by Galí and Gambetti (2015). The residuals from this longer sample are restricted to the sample for which the monetary surprises are available (1988M11-2011M12) and used in the external steps. The obtained impulse responses are shown in figure (44).[66] Compared to the IRFs for the sample 1988M11-2012M6 in figure (42), the negative stock price response is more pronounced and the increase in risk-premia is larger. These results can be explained with the fact that the perceived bubble period during the 1990s matters more strongly for the smaller sample, during which stock prices and risk-premia are less responsive. However, note that the F-statistic from the first stage with respect to the external steps is well below 10, so problems associated with weak instruments cannot be confidently excluded according to Stock, Wright and Yogo (2002).

[66]The lag length is set to $k = 9$ as suggested by Akaike's information criterion.

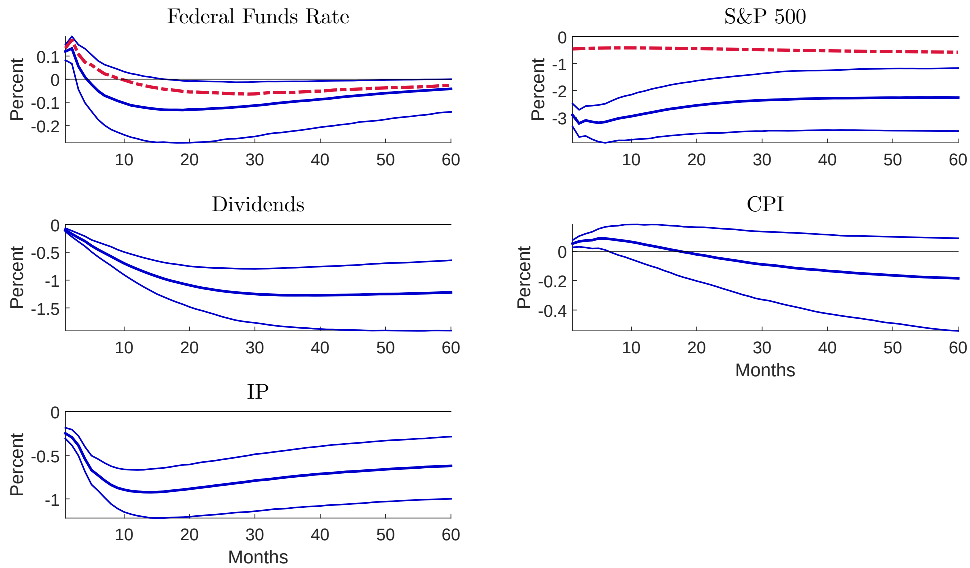


Figure 44: ***Impulse Response Functions - External Instrument Approach - 1960M1-2011M12.*** *IRFs to a 100 basis point surprise contractionary monetary policy shock. Median responses and 95% confidence bands are shown. The red dotted line in the plot of the Federal Funds rate is the real interest rate. The red dotted line in the plot of the S&P 500 shows the response of the stock price based on discounted dividends (see Appendix C.2). F-statistic: 5.40. Robust F-statistic: 5.48 with respect to the first stage regression.*

C.5 Data

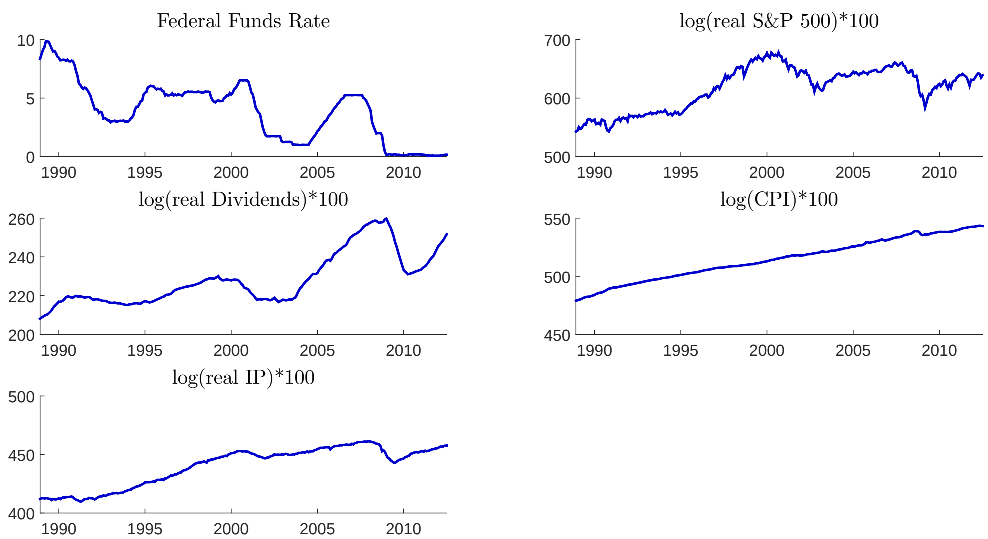


Figure 45: ***Data.*** *Data series in (log)-levels.*

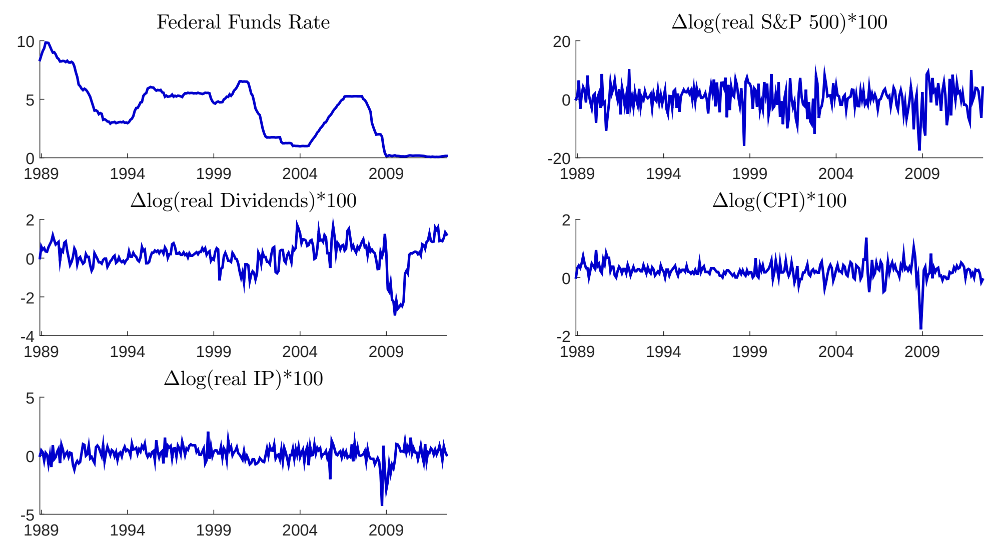


Figure 46: ***Data.*** *Data series in first-differences (except for the Federal Funds rate).*

C.6 Controlling for the Fed's Information Advantage

Regressor	$\mathbb{S}_t^k$
Constant	−0,010*
Y_t^k	0,013
Y_{t+1}^k	−0,018
Y_{t+2}^k	0,020**
Π_t^k	0,011
Π_{t+1}^k	−0,045***
Π_{t+2}^k	0,018
ΔY_t^k	0,001
ΔY_{t+1}^k	0.000
ΔY_{t+2}^k	−0,021**
$\Delta\Pi_t^k$	0,002
$\Delta\Pi_{t+1}^k$	0,017
$\Delta\Pi_{t+2}^k$	−0,019
Observations	162
R^2	0.12
F-statistic	1.62
Prob>F	0.09

Table 11: *The dependent variable is the series of monetary surprises in the current month's Federal Funds rate* $\mathbb{S}_t^k$ *around scheduled FOMC meeting* k*. The regressors are the differences between the Greenbook and the "Survey of Professional Forecasters" forecasts for inflation* Π^k *and real GDP* Y^k *with respect to the current, the next, and two quarters ahead and the change in those differences. The current quarter is the quarter in which meeting* k *takes place. Greenbook forecasts are prepared with respect to every scheduled FOMC meeting. The survey of professional forecasters is available on a quarterly frequency.*

*Notation: *** Significant at* 1 *percent, ** Significant at* 5 *percent, * Significant at* 10 *percent.*

C.7 Time Varying Impulse Response Functions Ω_t- Model

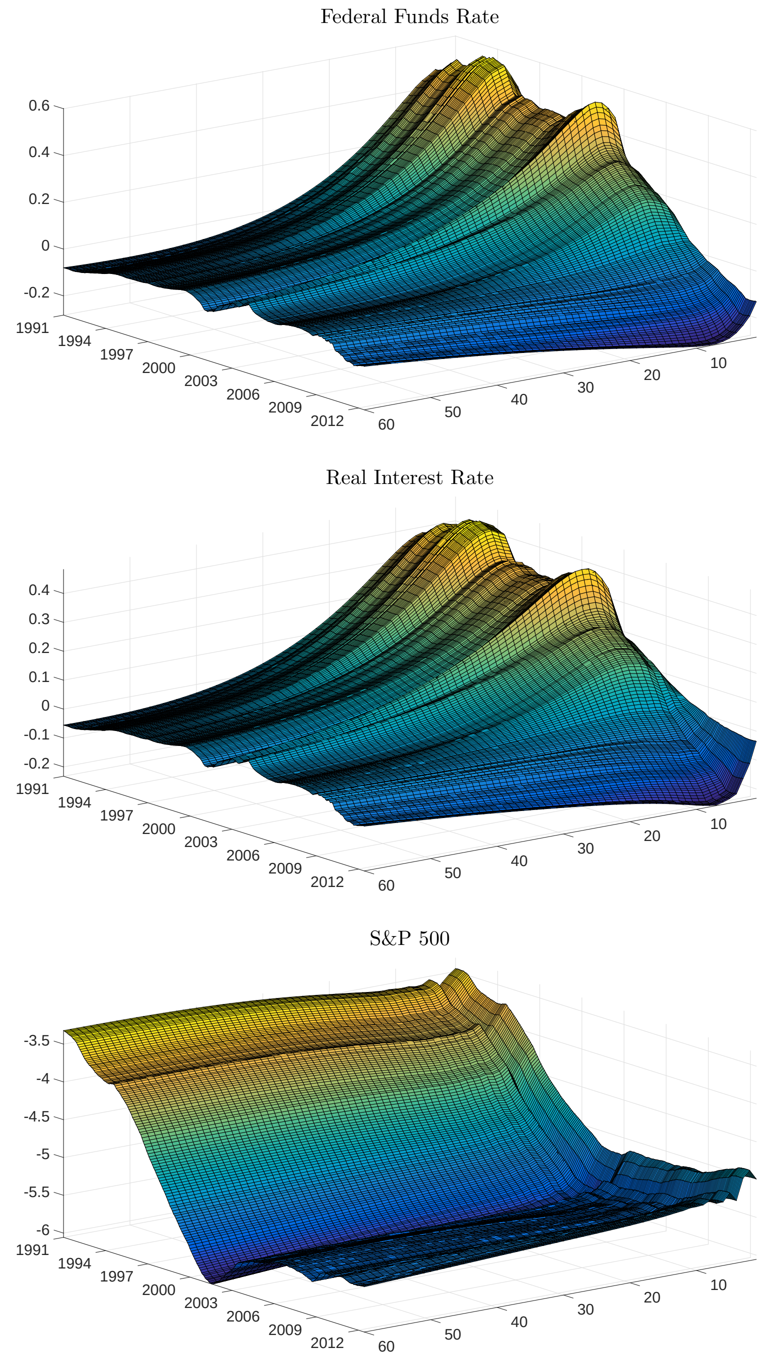


Figure 47: ***Time Varying Impulse Response Functions.*** *IRFs to a contractionary monetary policy surprise, normalized to the mean of the standard deviation of the residual from the Federal Funds rate equation. The responses are based on the posterior mean* $\overline{B}_t$ *for period* t *(see definition in equation (20)). Vertical axis: Percentage change. Front axis left: Years. Front axis right: Months (Horizon IRF).*

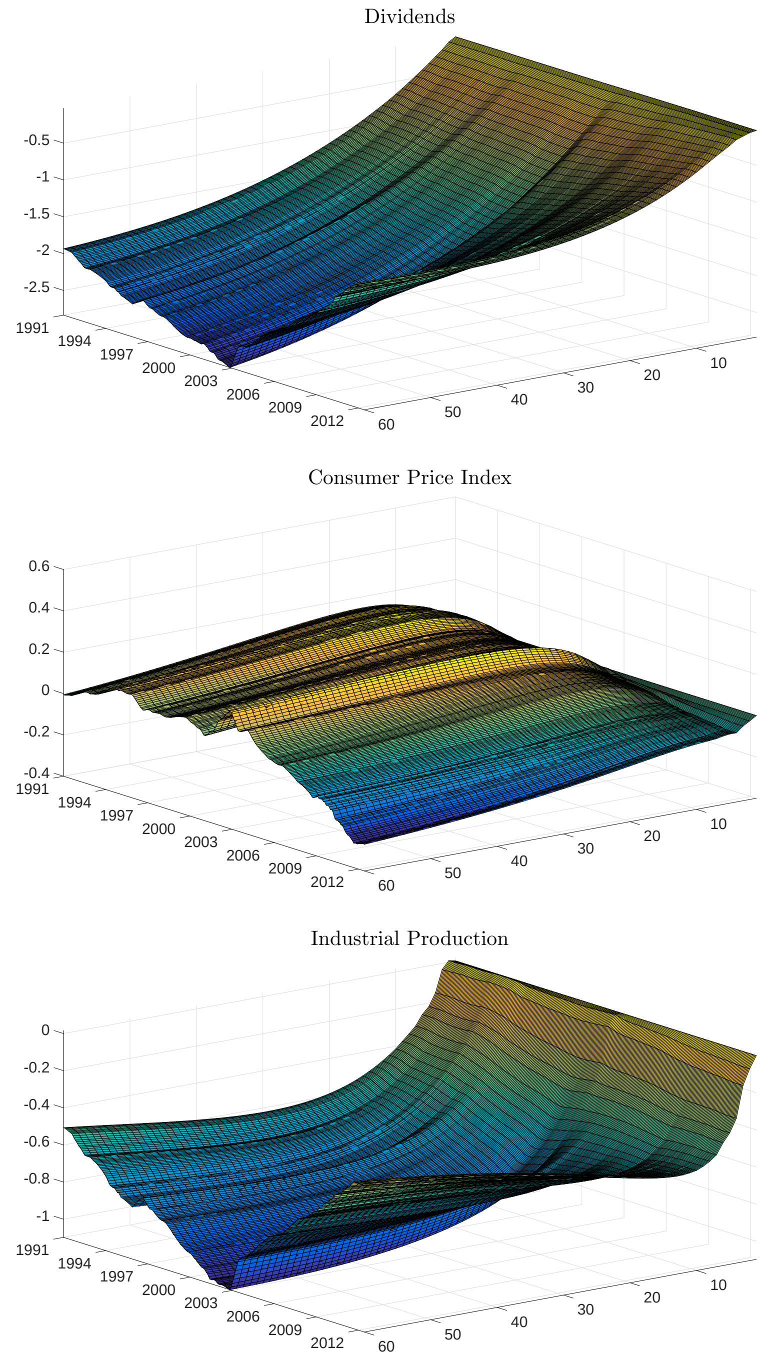


Figure 48: ***Time Varying Impulse Response Functions.*** *IRFs to a contractionary monetary policy surprise, normalized to the mean of the standard deviation of the residual from the Federal Funds rate equation. The responses are based on the posterior mean* $\overline{B}_t$ *for period* t *(see definition in equation (20)). Vertical axis: Percentage change. Front axis left: Years. Front axis right: Months (Horizon IRF).*

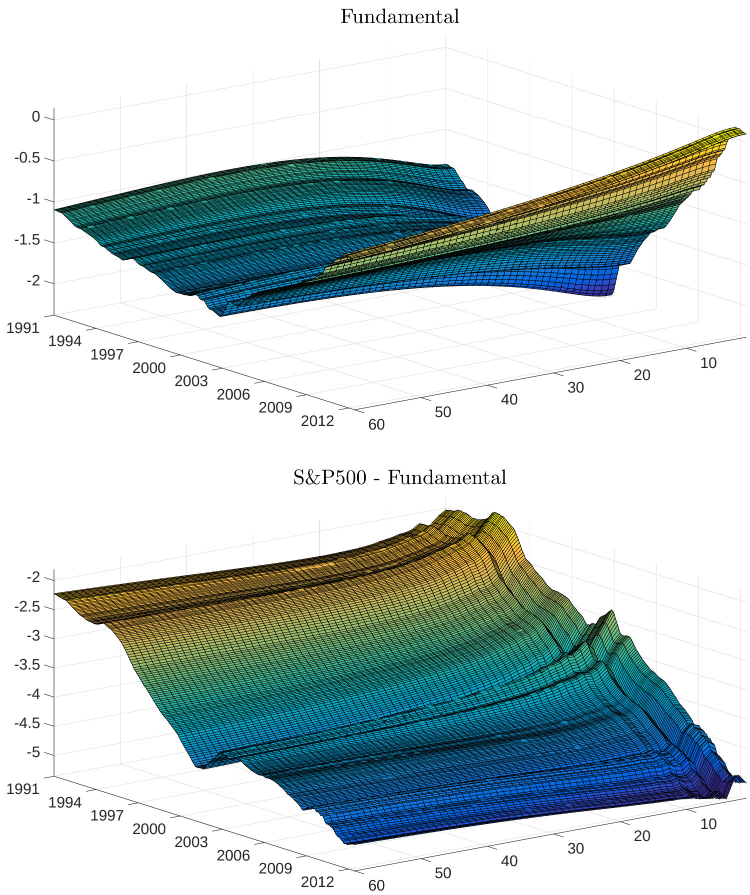


Figure 49: ***Time Varying Impulse Response Functions.*** *IRFs to a contractionary monetary policy surprise, normalized to the mean of the standard deviation of the residual from the Federal Funds rate equation. The responses are based on the posterior mean* $\overline{B}_t$ *for period* t *(see definition in equation (20)). Vertical axis: Percentage change. Front axis left: Years. Front axis right: Months (Horizon IRF).*

C.8 Robustness

C.8.1 Short-Run Restrictions

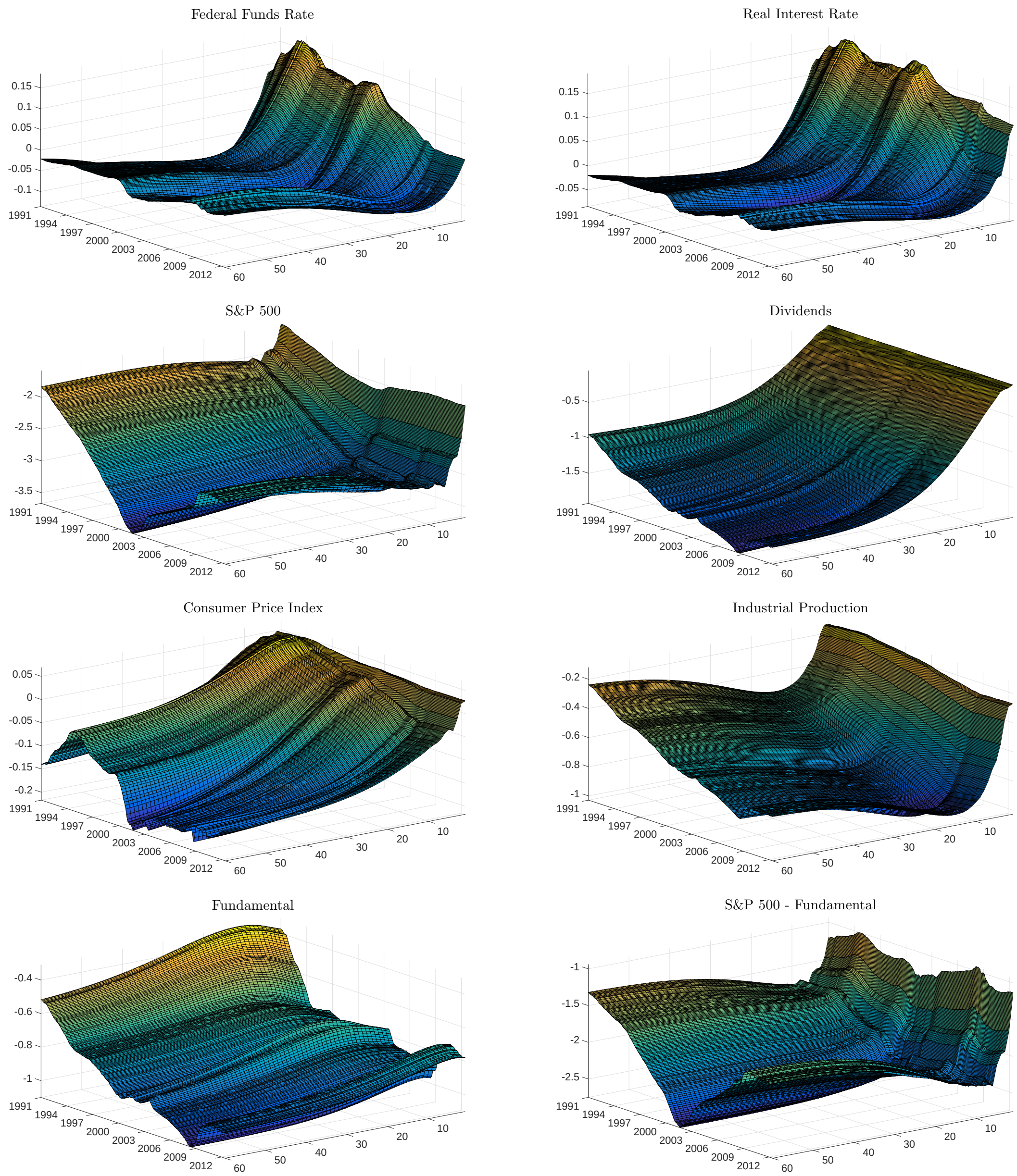


Figure 50: ***Time Varying Impulse Response Functions.*** *IRFs to a contractionary monetary policy surprise, normalized to the mean of the standard deviation of the residual from the Federal Funds rate equation. The responses are based on the posterior mean* $\overline{B}_t$ *for period* t *(see definition in equation (20)). Vertical axis: Percentage change. Front axis left: Years. Front axis right: Months (Horizon IRF).*

C.8.2 Excluding Great Recession

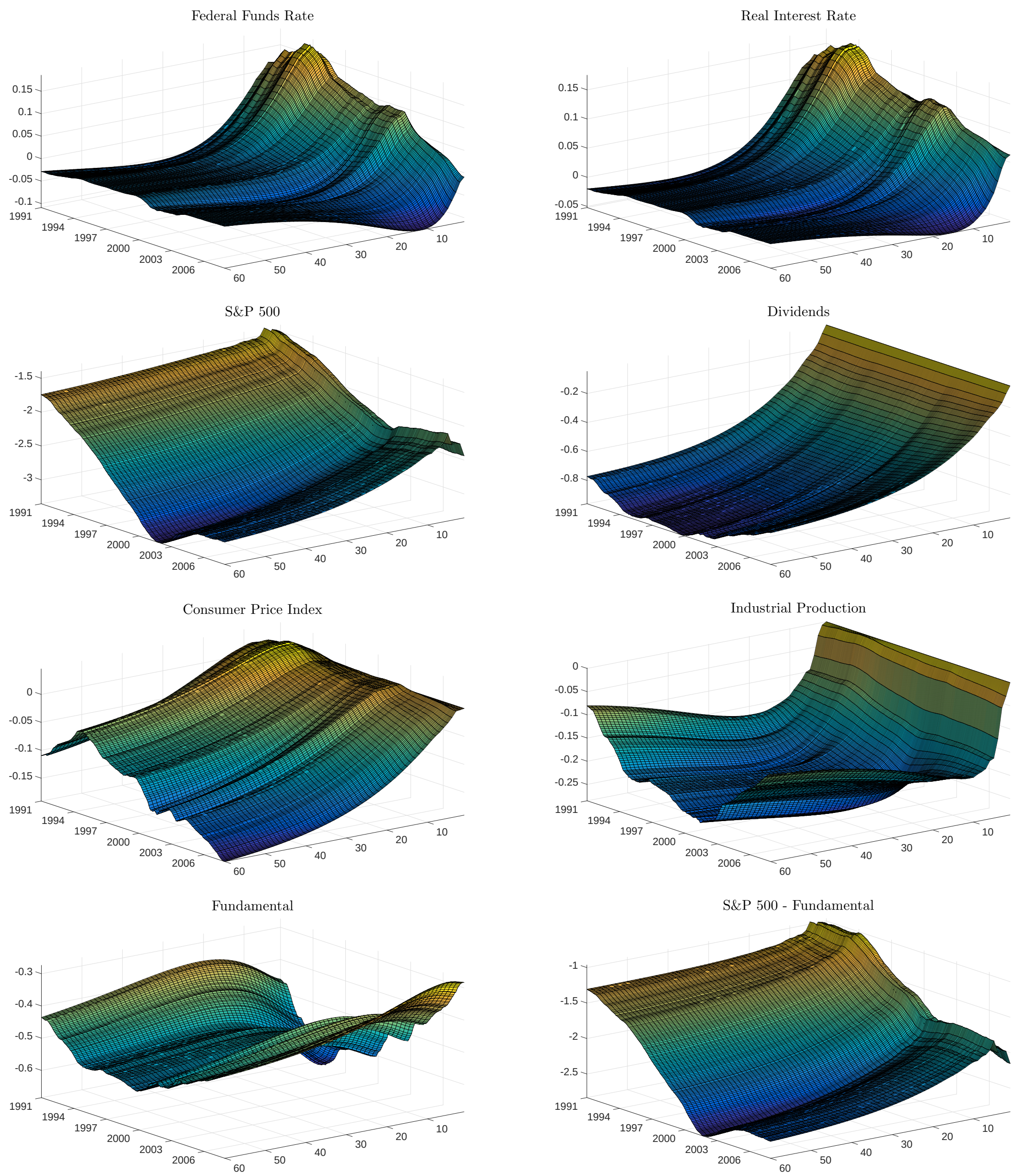


Figure 51: ***Time Varying Impulse Response Functions.*** *IRFs to a contractionary monetary policy surprise, normalized to the mean of the standard deviation of the residual from the Federal Funds rate equation. The responses are based on the posterior mean* $\overline{B}_t$ *for period t (see definition in equation (20)). Vertical axis: Percentage change. Front axis left: Years. Front axis right: Months (Horizon IRF).*

C.8.3 Priors

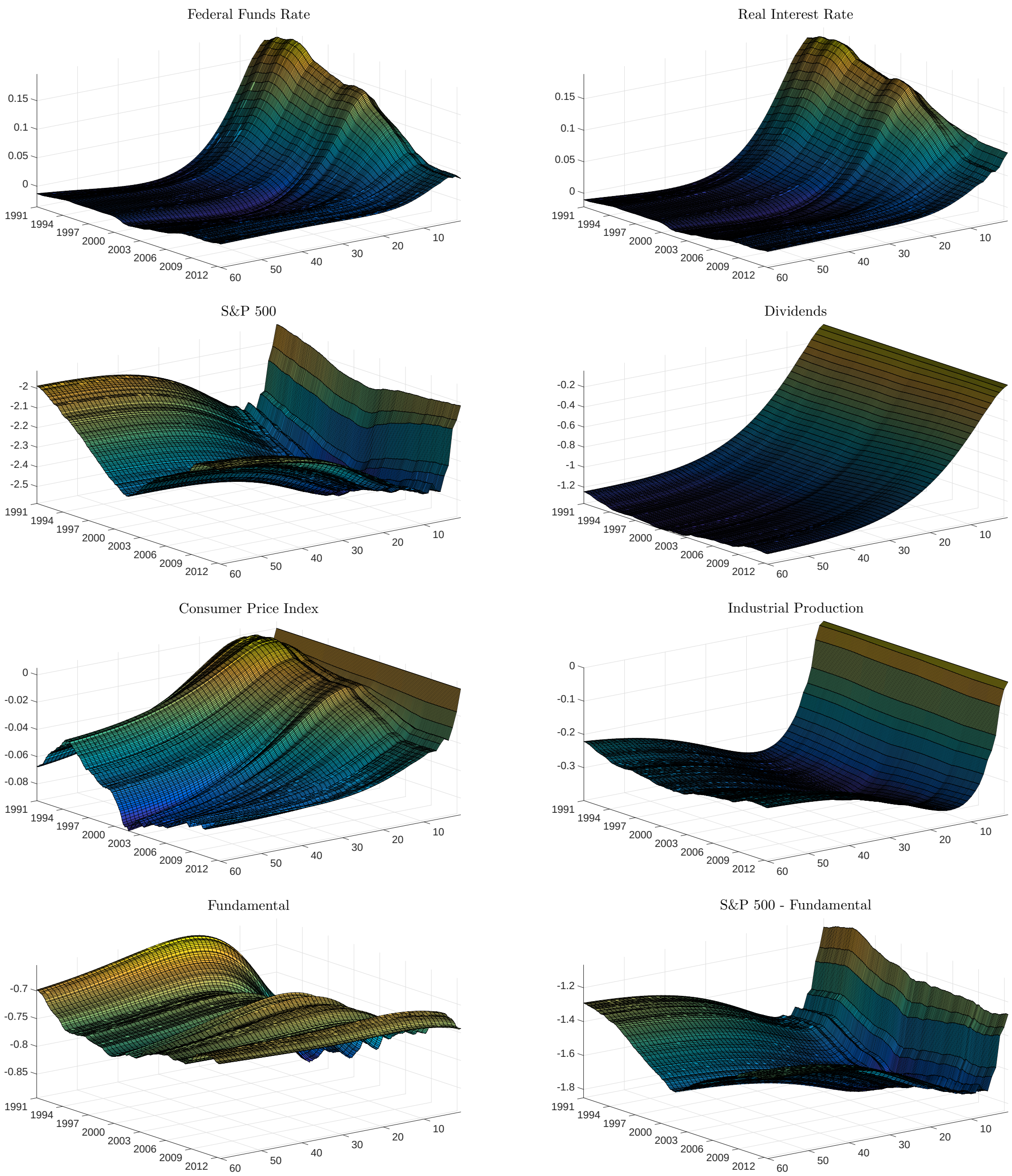


Figure 52: ***Time Varying Impulse Response Functions.*** *IRFs to a contractionary monetary policy surprise, normalized to the mean of the standard deviation of the residual from the Federal Funds rate equation. The responses are based on the posterior mean* $\overline{B}_t$ *for period* t *(see definition in equation (20)). Vertical axis: Percentage change. Front axis left: Years. Front axis right: Months (Horizon IRF).*

C.8.4 Futures Expiring after Current Period

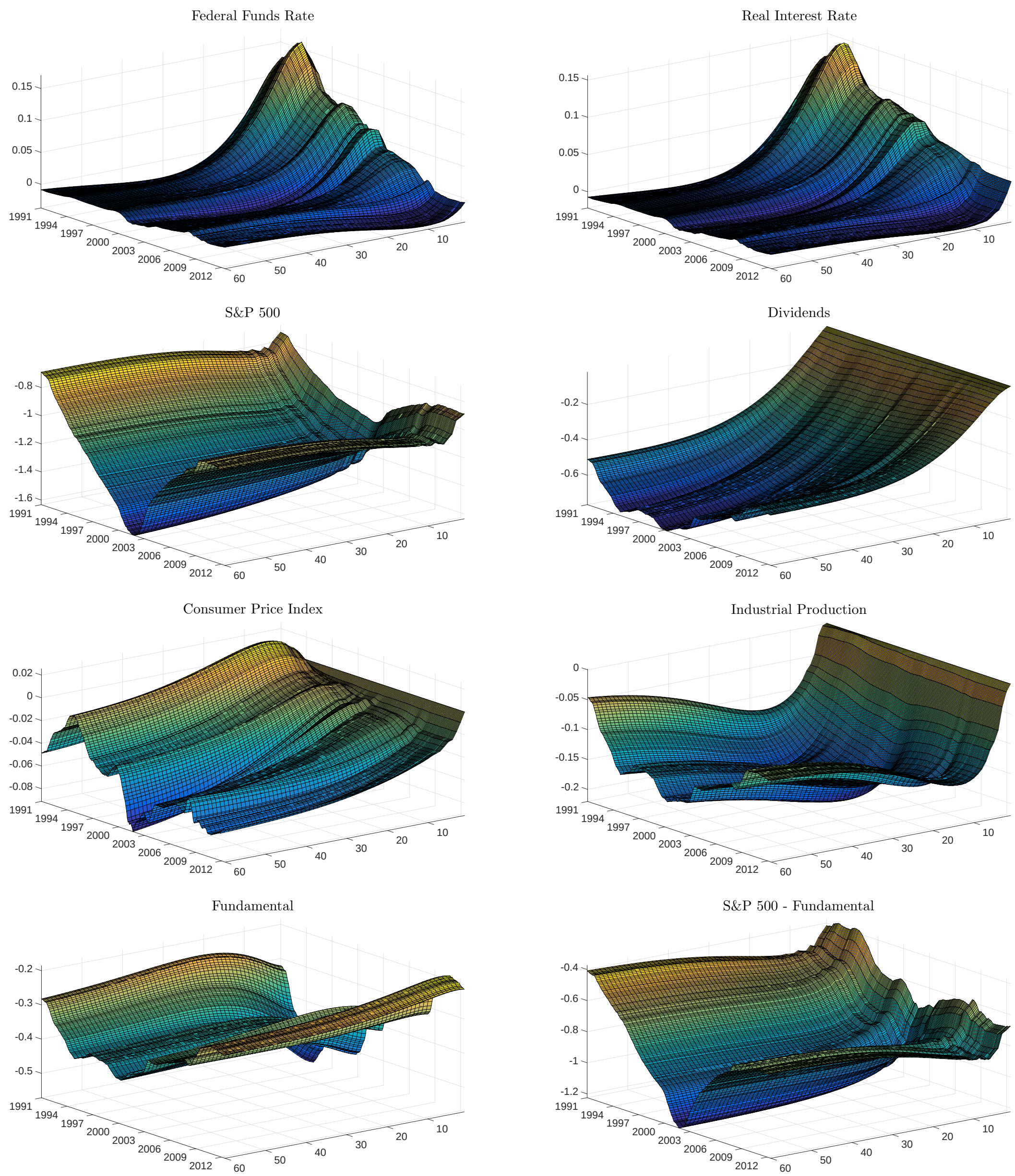


Figure 53: ***Time Varying Impulse Response Functions.*** *IRFs to a contractionary monetary policy surprise, normalized to the mean of the standard deviation of the residual from the Federal Funds rate equation. The responses are based on the posterior mean* $\overline{B}_t$ *for period* t *(see definition in equation (20)). Vertical axis: Percentage change. Front axis left: Years. Front axis right: Months (Horizon IRF).*

C.8.5 The Fed's Information Advantage

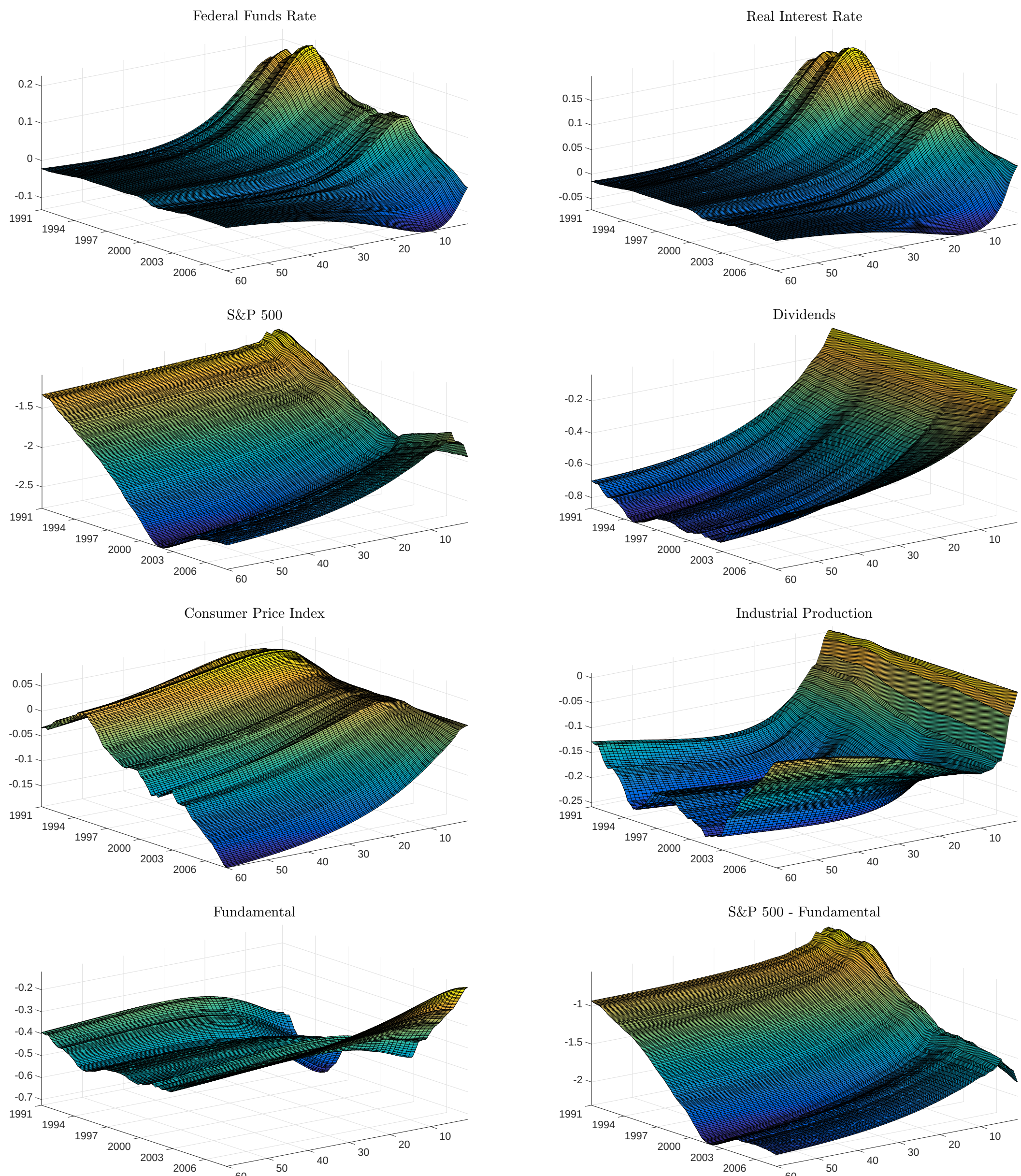


Figure 54: ***Time Varying Impulse Response Functions.*** *IRFs to a contractionary monetary policy surprise, normalized to the mean of the standard deviation of the residual from the Federal Funds rate equation. The responses are based on the posterior mean* $\overline{B}_t$ *for period* t *(see definition in equation (20)). Vertical axis: Percentage change. Front axis left: Years. Front axis right: Months (Horizon IRF).*

C.8.6 Unscheduled Meetings

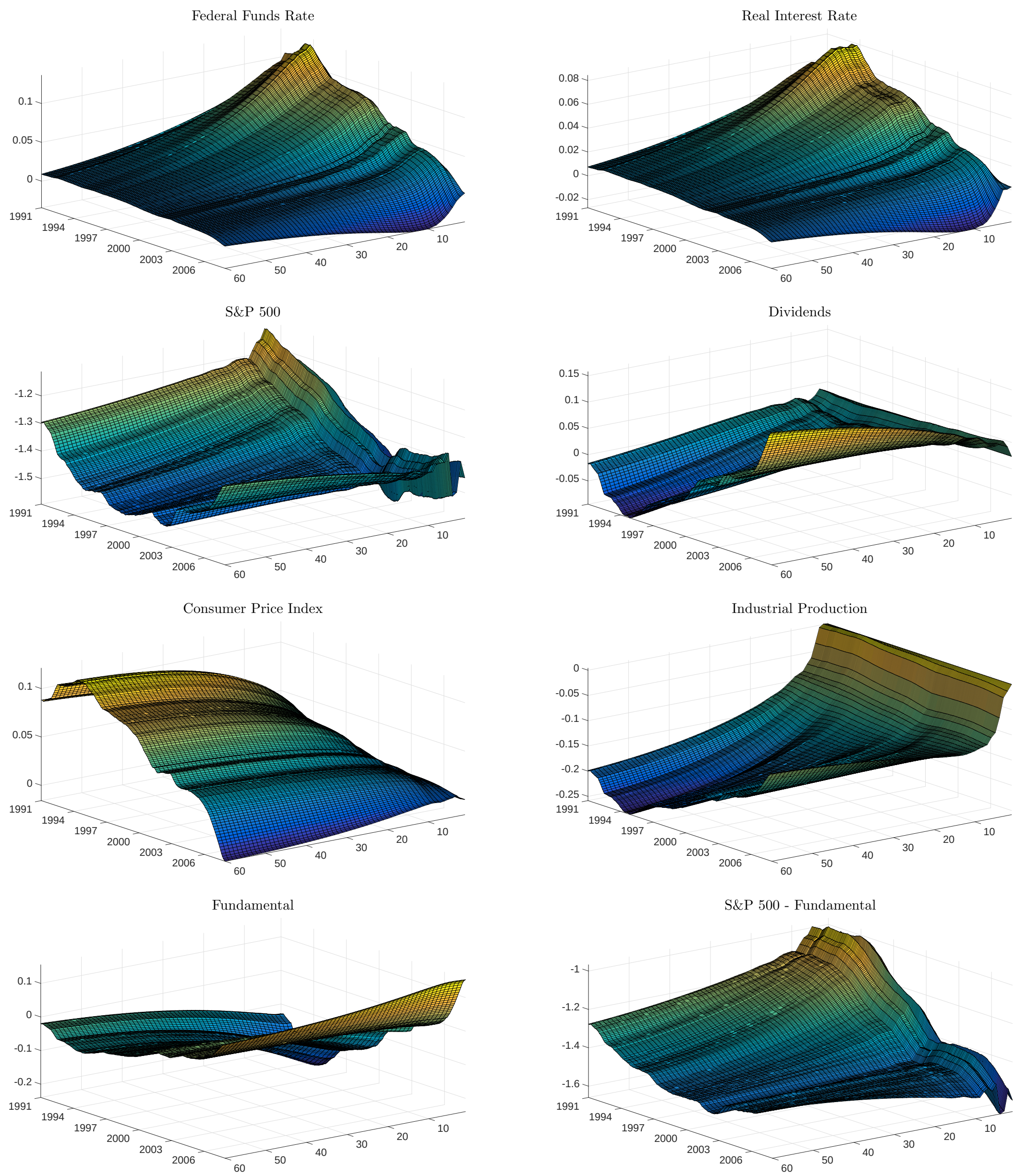
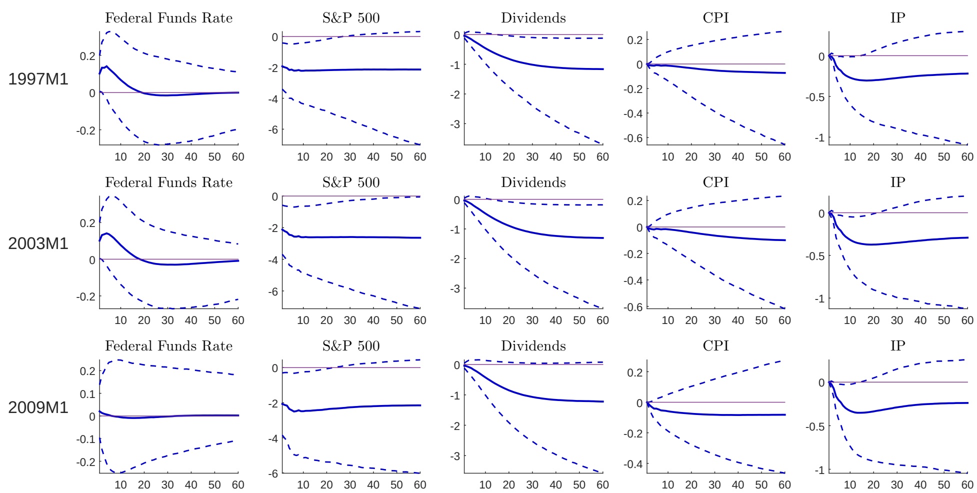


Figure 55: ***Time Varying Impulse Response Functions.*** *IRFs to a contractionary monetary policy surprise, normalized to the mean of the standard deviation of the residual from the Federal Funds rate equation. The responses are based on the posterior mean* $\overline{B}_t$ *for period t (see definition in equation (20)). Vertical axis: Percentage change. Front axis left: Years. Front axis right: Months (Horizon IRF).*

C.9 Time Varying Impulse Responses - Confidence Bands

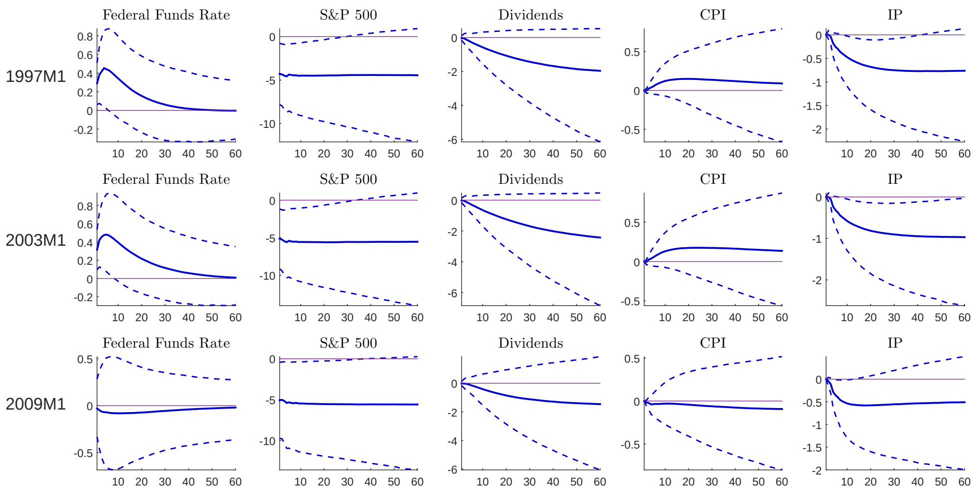
This section shows time varying IRFs and 95% confidence bands for the Ω-model and the Ω_t-model for selected periods.[67] The selected periods are 1997M1, 2003M1, and 2009M1 which are representative for the 90s boom period, the recession in the early 2000s, and the recent zero-lower bound episode.

Figure 56: **Time Varying Parameter VAR - Ω**



[67]IRFs to a contractionary monetary policy surprise, normalized to the mean of the standard deviation of the residual from the Federal Funds rate equation. The responses are based on the posterior mean $\overline{B}_t$ for period t (see definition in equation (20)).

Figure 57: **Time Varying Parameter VAR - Ω_t**



C.10 Time Varying Impulse Responses - 2D

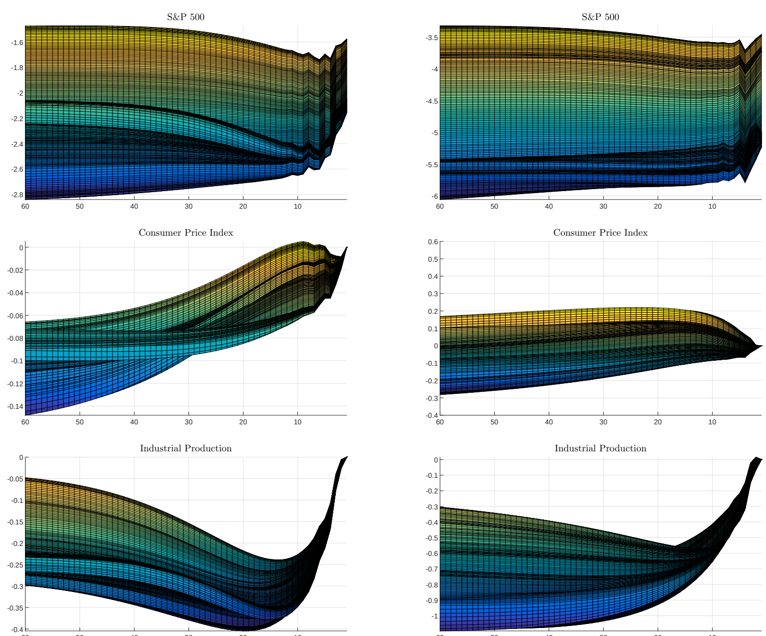


Figure 58: ***Time Varying Impulse Response Functions in 2D.*** *X-axis: Horizon IRF. Y-Axis: Percent Change. Left: Time Varying Parameter VAR - Ω. Right: Time Varying Parameter VAR - Ω_t.*

D Appendix to Chapter III

D.1 Derivation Steady State Conditions

Assume $b > 0$. Express Proposition 1. in steady state

$$v = R^K + \beta v(1-\delta) + \pi(\beta v - 1)(\beta v\xi + R^K) \quad (91)$$

$$b = \beta\left[b + \pi(\beta v - 1)b\right] \quad (92)$$

$$K = K(1-\delta) + \pi\left[\beta(v\xi K + b) + R^K K\right] \quad (93)$$

Rearranging equation (92) gives

$$v = \frac{1}{\beta}\left((\frac{1}{\beta} - 1)\frac{1}{\pi} + 1\right) \quad (94)$$

Rearranging equation (91) gives

$$R^K = \frac{v\left(1 - \beta(1-\delta)\right)}{\left(1 + \pi(\beta v - 1)\right)} - \frac{\beta\pi v(\beta v - 1)}{\left(1 + \pi(\beta v - 1)\right)}\xi \quad (95)$$

Rearranging equation (93) gives

$$\frac{b}{K} = \frac{\delta}{\pi} - R^K - \beta v\xi \quad (96)$$

Using equations (94) and (95) in (96) gives the condition in Proposition 2.

Similarly, assume $b = 0$. Express Proposition 1. in steady state

$$v = R^K + \beta v(1-\delta) + \pi(\beta v - 1)(\beta v\xi + R^K) \quad (97)$$

$$K = K(1-\delta) + \pi\left[\beta v\xi K + R^K K\right] \quad (98)$$

Rearranging equation (98) gives

$$R^K = \frac{\delta}{\pi} - \beta v\xi \quad (99)$$

Using equation (99) in (97) and rearranging gives

$$\beta v = \frac{\frac{\delta}{\pi} - \delta}{\frac{1}{\beta} + \xi - 1}$$

from which the condition in Proposition 3. follows.

D.2 Model Equations

Household

$$\mathbb{E}(\Lambda_{t,t+1}\frac{(1+i_t)}{\Pi_{t+1}}) = 1 \tag{100}$$

$$\Lambda_{t,t+1} = \beta\left(\frac{C_{t+1} - \frac{N_{t+1}^{1+\phi}}{1+\phi}}{C_t - \frac{N_t^{1+\phi}}{1+\phi}}\right)^{-\gamma} \tag{101}$$

$$w_t = \chi N_t^{\phi} C_t^{\gamma} \tag{102}$$

Firms

$$Y_t = \Delta_t {K_t}^{\alpha} N_t^{1-\alpha} \tag{103}$$

$$I_t = \mathbb{E}\left[\Lambda_{t,t+1}V_{t+1}(\xi K_t)\right] + R_t^K K_t \tag{104}$$

$$V_t = v_t K_t + b_t \tag{105}$$

$$R_t^K = P_t^m \alpha K_t^{\alpha-1} N_t^{1-\alpha} \tag{106}$$

$$w_t = P_t^m (1-\alpha) K_t^{\alpha} N_t^{-\alpha} \tag{107}$$

$$v_t = R_t^K + \mathbb{E}\left[\Lambda_{t,t+1}v_{t+1}(1-\delta) + \pi(\Lambda_{t,t+1}v_{t+1} - 1)(\Lambda_{t,t+1}v_{t+1}\xi + R_t^K)\right] \tag{108}$$

$$b_t = \mathbb{E}\left[\Lambda_{t,t+1}(b_{t+1} + \pi(\Lambda_{t,t+1}v_{t+1} - 1)b_{t+1})\right] \tag{109}$$

Monetary Policy and Sticky Prices

$$i_t = (1-\rho^m)(i^{SS} + \phi_\pi log\Pi_t) + \rho^m i_{t-1} + \epsilon_t^m \tag{110}$$

$$\frac{F_t}{Z_t} = \frac{\epsilon-1}{\epsilon}(\frac{1-\theta\Pi_t^{\epsilon-1}}{(1-\theta)})^{\frac{1}{1-\epsilon}} \tag{111}$$

$$F_t = P_t^m Y_t + \mathbb{E}[\theta\Lambda_{t,t+1}\Pi_{t+1}^{\epsilon}F_{t+1}] \tag{112}$$

$$Z_t = Y_t + \mathbb{E}[\theta\Lambda_{t,t+1}\Pi_{t+1}^{\epsilon-1}Z_{t+1}] \tag{113}$$

$$\Delta_t = ((1-\theta)(\frac{1-\theta\Pi_t^{\epsilon-1}}{(1-\theta)})^{-\frac{\epsilon}{1-\epsilon}} + \theta\frac{\Pi_t^{\epsilon}}{\Delta_{t-1}})^{-1} \tag{114}$$

Market Clearing

$$K_{t+1} = (1-\delta)K_t + \pi I_t \tag{115}$$

$$Y_t = C_t + \pi I_t \tag{116}$$