A Structural Framework to Analyse the Financial Stability Tool Net Stable Funding Ratio

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[1] Special thanks to my supervisors Prof. Dimitrios P. Tsomocos and Prof. Sophocles Mavroeidis, who offered tremendous support for my work and provided valuable guidance and feedback in shaping both the theoretical derivations and policy experiments. Comments from Prof. Kwangwon Ahn, Prof. Udara Peiris, Dr. Li Lin and Dr. Dominic Quint were extremely helpful. I'm also thankful to Prof. Martin Ellison and Prof. Francesco Zanetti for their advice, and also seminar participants for my other empirical work on the Net Stable Funding Ratio at the Bank of England. However, all remaining errors are mine. Please send further comments to xuan.wang@sbs.ox.ac.uk..

Abstract

This paper builds a dynamic stochastic general equilibrium (DSGE) to analyse the new financial stability tool Net Stable Funding Ratio (NSFR). It complements the current literature that uses DSGE to model the banking sector in three ways. Firstly, we introduce endogenous maturity mismatch in the heterogeneous banking sector, where the retail bank uses short-term deposits to provide the firms with long-term corporate loans. Secondly, hitherto neglected components such as endogenous default and money via cash-in-advance (CIA) constraints are incorporated so that liquidity and default are the reasons for the influence of money injections on real economic variables. Lastly, the model analyses the macro-prudential instrument Net Stable Funding Ratio (NSFR), designed to reduce the overall maturity mismatch. With a calibrated DSGE model, we micro-found default and maturity mismatch and analyse how they feed into real economic variables, particularly the term structure of various interest rates, and we have found that a fall in maturity mismatch typically reduces the default rates of the firms and the retail bank. Moreover, we simulate the quantitative policy impact of the macro-prudential policy tool NSFR on the economy and search for optimal policy reaction functions that induce the most welfare gains.

Keywords: financial stability, maturity mismatch, default, NSFR, macro-prudential, welfare analysis

Contents

1.Introduction

‘It is just wrong to say that this financial crisis caught modern macroeconomists by surprise. That statement does a disservice to an important body of research to which responsible economists ought to be directing public attention.’

----Thomas Sargent

Despite numerous financial innovations and the vicissitudes in the capital market, the 2007-2009 financial crisis was hardly a new occurrence, and the contributing factors are not entirely unfamiliar to us. There has been a substantial growth in literature that focuses on the risky nature of the capital market since the Great Depression, and the recent crisis has driven more valuable and creative work in this area. In our view, this area of research includes, but is not limited to, three major topics: crisis management, risk identification and pre-crisis risk management.

In crisis management, one of the important lessons from the Great Depression is the prompt involvement of the central bank, which acts to lower the interest rate and boost demand. Fisher’s debt-deflation mechanism illustrates the downward spiral, which occurs when the central bank fails to intervene at the outset of the crisis; the over-indebtedness of the banking system precipitates deflation, furthering default and exacerbating the crisis. Conventional wisdom has it that the central bank provides liquidity during a crisis and keeps the price level in check during normal times. Although the Great Moderation may seem to substantiate the view that a good inflation-targeting policy in the mid-1980s led to a decline in aggregate economic volatility, inflation targeting is no panacea to escalating systemic risk in the credit market or banking system, and providing liquidity during a crisis is crisis management at most.

Parallel to the research on crisis management, another body of literature has focused on the identification of the risks in the financial system through the lens of game theory and principal-agent models, some of which are incorporated into the real business cycle (RBC) framework, such as Kareken and Wallace (1978), Mankiw (1986), Kiyotaki and Moore

(1997), Carlstrom and Fuerst (1997), Bernanke, Gertler and Gilchrist (1999), Iacoviello (2005), and Gertler and Kiyotaki (2009). This group of research analyses the frictions in the financial market and how the frictions feed into the real economy, generating the financial accelerator effect, and it points to the direction for policies to tackle these frictions. However, this group of research has not formally incorporated the specific implementations of policies into the canonical DSGE framework and analysed the policies' quantitative impacts from a pre-crisis risk management perspective.

Thus, as the 2007-2009 financial crisis has taught us, apart from the monetary instrument, regarding which the canonical DSGE and New Keynesian models have offered many policy prescriptions, we also need a set of macro-prudential instruments for pre-crisis risk management in the banking system. Way before the 2007-2009 financial crisis, existing research had forecasted the volatile nature of the financial market (i.e. risk-identification), but it was the recent crisis that prompted policy-makers to formally place macro-prudential policies on the research agenda; and DSGE has provided insight in the impact of macro-prudential policy implementation on the macroeconomic system and financial stability. Our paper contributes to this body of literature on macro-prudential policy for pre-crisis management purposes, and we focus on two major frictions in the financial market, namely default and excessive maturity mismatch, by using DSGE to model the implementation of a particular macro-prudential tool that reduces the excessive maturity mismatch of the banking system.

Prior to the 2007-2009 crisis, banks were engaging in activities with an increasing severity in maturity mismatch, relying more on short-term funding and illiquid assets to generate higher profits - a practice that brings an inherent risk to the bank business models. If the bad future state is realised, short-term creditors pull out their liquidity from the banks, and such banks become vulnerable and may be unable to roll over their borrowings (Diamond and Rajan 2009; Brunnermeier 2009; Acharya and Merrouche 2010; Huang and Ratnovski 2011). Upon investigation, we discovered that the most troubled banks in the financial crisis had serious mismatch issues on their balance sheets, as is the case with the three stand-alone US investment banks (Lehman Brothers, Merrill Lynch and Bear Stearns) and Northern Rock in the UK. Figure 1 provides a glimpse of the maturity structure of banks' balance sheets, where real estate loans increased tremendously against total bank assets from the end of 1998 to 2006. Moreover, banks have shifted away from stable deposit funding to high-turnover liabilities with shorter maturities. If we assume a roughly constant term structure of the banks' other assets, then Figure 1 suggests that assets, whose underlying loans could have terms as long as 30 years, are backed by liabilities with much shorter maturities. The marginal gains from holding long-term assets against short-term liabilities can be attractive since long-term assets generally pay higher term premiums, but such excessive maturity mismatch could become obstacles for banks to honour their obligations, leading to more severe default, particularly in the case of a liquidity shock.

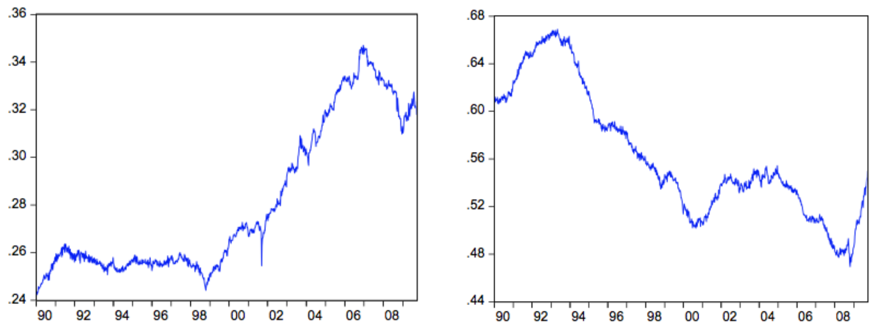

Figure 1: Real estate loans to bank assets (left); Net deposit to bank liabilities (right)
Source: Young, Wiseman and Hogan (2013); *Original source:* Federal Reserve, H.8 Assets and Liabilities of Commercial Banks in the United States. Weekly data.

Regarding the default choice of borrowing agents, particularly in the banking sector, regulatory authorities have been conveying the importance of less government bail-out and more bail-in of failing banks in the future, thus aggravating the non-pecuniary default penalty on the banks and hopefully reducing defaults. Moreover, the response from regulatory authorities to reduce maturity mismatch has become more specific. In December 2010, the Basel Committee on Banking Supervision (BCBS) published the Basel III documents 'Basel III: A Global Regulatory Framework for More Resilient Banks and Banking Systems' and 'Basel III: International Framework For Liquidity Risk Management, Standards and Monitoring'. Out of the two liquidity requirements[2], Net Stable Funding Ratio (NSFR) is most relevant to reducing excessive maturity mismatch as it addresses funding risks and is designed to promote structural changes in the risk profiles of banks - toward more stable longer-term funding of assets and away from short-term funding mismatches.

In summary, our paper uses a structural model to incorporate two financial frictions, endogenous default and maturity mismatch, studies their relationship, and analyses the optimal implementation and impact of the macro-prudential policy NSFR on the reduction of excessive maturity mismatch at the aggregate level. Since our paper analyses frictions in the financial market and focuses on a specific macro-prudential policy tool that deals with financial frictions, it formally analyses the interactions between the macro-prudential policy and monetary policy, and complements the New Keynesian literature, which basically assumes a frictionless financial market and focuses mainly on the use of monetary policy rule to manage the economy.

2 The other one is the Liquidity Coverage Ratio (LCR), which addresses liquidity risk and is designed to ensure banks have adequate liquidity to survive one month of stressed funding conditions. But this ratio is not the focus of this paper.

2. Literature Review

The literature review consists of four parts. Part 1 provides an overview of literature on financial frictions in the macroeconomic context. Part 2 and Part 3 discuss the literature on the two major frictions of the 2007-2009 crisis, namely, default and excessive maturity mismatch. Part 4 summarises our contribution to literature.

2.1. Financial Frictions in the Macroeconomic Context

Prior to the financial crisis, economists had begun identifying risks and analysing frictions in the financial market. Kareken and Wallace (1978) discuss the problem of moral hazard in the banking system, in which deposit insurance induces the banks to undertake more risks, and Mankiw (1986) highlights adverse selection problems in investment decisions of the bankers. However, these papers fail to incorporate these frictions in a dynamic general equilibrium, so their quantitative impacts and risks on macroeconomic variables are unknown. Kiyotaki and Moore (1997), Carlstrom and Fuerst (1997), Bernanke, Gertler and Gilchrist (1999), Iacoviello (2005), and Gertler and Kiyotaki (2009) show how financial frictions augment the propagation of shocks in the otherwise canonical RBC DSGE models, so that the transmission mechanism of how specific frictions feed into macroeconomic variables can be examined.

Nonetheless, the abovementioned literature is categorised as 'risk identification'; it merely incorporates the friction from the 'principal-agent' problem, and do not model the specific structure of the banking system and credit market. Moreover, it neglects the formal analysis of policy prescriptions and their relevant implementations. These gaps are addressed in our paper, which examines the heterogeneous banking system and the credit market by focusing on two major frictions that manifested in the recent financial crisis, excessive maturity mismatch and endogenous default; we further discuss optimal implementation of relevant macro-prudential policy from a pre-crisis risk management perspective.

2.2. On Endogenous Default

Regarding endogenous defaults of the borrowing agents, our paper follows Ahn and Tsomocos (2012), De Walque et al (2010), Goodhart et al (2006), and Dubey, Geanakoplos, and Shubik (2005). The visionary works by Bernanke, Gertler and Gilchrist (1998) and Iacoviello (2005) analysed the interaction between the financial market and the rest of the economy by introducing credit and collateral requirements. However, these models do not assign any role to financial intermediaries such as banks and assume that credit transactions go through the market directly, while financial intermediaries, i.e. banks, do exist and do default, and a significant degree of heterogeneity exists in them. Conventional models have neglected these factors, all of which contribute to frictions in the economy, and if captured well, would shed light on the transmission mechanism in the interbank market and explain the contagion in the financial crisis. Ahn and Tsomocos (2012) introduced two financial frictions: endogenous default and money via CIA constraints. Endogenous default arises as an equilibrium phenomenon, because borrowing agents are allowed to choose what proportion of outstanding debts to repay, and the cost of default is modelled by a penalty that reduces utility. The possibility of default on any debt obligation underscores the necessity of cash-in-advance (CIA) constraints, which capture the liquidity effect and its interaction with default to affect the real economy.

2.3.On Maturity Mismatch

One of the earliest models to describe maturity mismatch, or maturity transformation, was proposed by Diamond and Dybvig (1983); it characterises maturity transformation as the fundamental function of the banking system and suggests that deposit insurance could contribute to the social-optimal equilibrium. However, this research leaves out moral hazard and disregards the risk of excessive maturity mismatch. The recent financial crisis has reminded us of the importance of understanding the frictions and risks of excessive maturity mismatch and the necessity of implementing relevant policy prescriptions. Accordingly, the crisis has helped to generate literature on the frictions of excessive maturity mismatch from a macro-perspective, which speaks in favour of public intervention to restore financial stability, and supports the implementation of NSFR.

The first systemic friction of maturity mismatch relates to the interconnectedness of financial institutions. Since banks are interconnected, if a bank begins hoarding liquidity by withdrawing from the interbank market, other banks have to reduce their assets even though their operations may be sound. If other banks are short of liquid assets, a fire sale happens or bankruptcy, in the worst-case scenario, happens. Morris and Shin (2008) analyse the potential consequences of interconnectedness and argue for structural liquidity requirements as a complement to risk-based capital requirements to constrain the composition of assets, since the risk-based capital requirements fail to distinguish between the inherent riskiness of an asset and its systemic importance. Similarly, Ansgar Walther (2014) expounds on the excessive systemic risk that is created by banks through leverage and maturity mismatch, and explains how capital and maturity regulation are complementary in restoring financial stability.

The second systemic friction of maturity mismatch is the time inconsistency faced by governments and regulators when a liquidity crisis occurs, and this is analysed by Farhi and Tirole (2012) from a game theory perspective. Farhi and Tirole argue that the interest-rate policy is a blunt instrument since it is only imperfectly targeted to the institutions they try to rescue. Conventionally, economic downturns call for public policy to help financial institutions weather the negative shock by lowering the benchmark rate (the federal funds rate in the US case) and pumping more liquidity into the banking system. The central bank supplies too much liquidity in the time-consistent outcome, while the low rate benefits financial institutions engaging in maturity mismatch and its effects apply to the entire economy. This scenario generates strategic complementarities in balance-sheet riskiness choices, which manifest themselves in the increased willingness of banks to take on more liquidity risks for higher profits - the awareness that other banks are highly mismatched for higher profits may create an expectation for government and regulators to implement a socially costly rescue plan if a systemic liquidity crisis hits, and would influence a bank to rationally be mismatched as well. Their theory brings support to the view that authorities in the recent crisis had few options but to lower the interest rate to weather the negative shocks, and that the crisis should have been contained *ex ante* through more careful macro-prudential policies. Their framework also suggests the potential value of a structural macro-prudential policy in which the regulators consider the overall transformation of maturities in the financial institutions. In a nutshell, imposing a structural macro-prudential liquidity requirement such as NSFR can potentially overturn financial institutions' expectations for accommodative policy and socially costly rescue plans, reducing the effect of strategic complementarity in its engagement of excessive maturity mismatch, and possibly restoring financial stability.

However, the existing literature on maturity mismatch mainly provides policy prescriptions, neither including an analysis on how policy should be implemented optimally alongside the fluctuations of business cycles, nor explaining how maturity mismatch feed into real economic variables. The only work to our knowledge, examines how maturity mismatch feeds into the real economy in a dynamic general equilibrium, is the paper by Andreasen, Ferman and Zabczyk (2013). Andreasen et al assume that firms in every period face a constant probability of being unable to adjust capital stock, leading to firms in need of loans with longer maturities than household deposits. This Calvo-style capital-reoptimisation friction rationalises firms' needs of corporate loans with longer maturities, and matches the stylised fact that firms invest in a lumpy fashion as outlined in the literature on non-convex investment adjustment costs (Caballero and Engel 1999; Cooper and Haltiwanger 2006). However, since this friction is not a choice of the banks, it is difficult to impose a macro-prudential maturity mismatch regulatory requirement for the banks, i.e. NSFR, let alone simulate its impact on the real economy.

2.4. Our Contribution to Literature

Although Andreasen et al.'s paper uses a DSGE framework to analyse the impact of maturity mismatch on macroeconomic variables, it leaves no scope to analyse the macro-prudential policy (NSFR) that is designed to reduce maturity mismatch. Therefore, our paper fills the gap in the above two strands of literature because it not only incorporates maturity mismatch into a DSGE framework, but also adds policy prescription and discusses optimal implementation of the relevant macro-prudential policy alongside the fluctuation of business cycles from a pre-crisis risk management perspective. Moreover, our paper models endogenous default and money via CIA constraints, so that we can further analyse how maturity mismatch and the relevant macro-prudential policy (NSFR) interacts with default and monetary policy. It should be noted that our understanding of the macro-prudential policy NSFR would relate only to business cycle properties. While this is in line with a part of the literature based mainly on DSGE models, it is much less nuanced than the approach of many policymakers, who see macro-prudential policy as a tool designed to prevent systemic risk in the financial sector. To analyse macro-prudential policy from this perspective, it would be more appropriate to use the principal-agent model as suggested by Farhi and Tirole (2012). DSGE models are helpful to analyse short-term transmission mechanisms in the system and would exhibit the impact of macro-prudential tools on business cycles from a pre-crisis risk management perspective. Our findings on the macro-prudential policy NSFR should be interpreted having the above characteristics in mind.

The rest of the paper is organised as follows: Section 3 sets up the model and equilibrium conditions; Section 4 provides equilibrium analysis and propositions on the Fisher Effect, Term Structure of Interest Rates, Money Non-Neutrality, On-the-Verge Conditions and Interplay between Maturity Mismatch and Default; Section 5 calibrates the model; Section 6 performs quantitative analysis and probes how various shocks translate into the real economy; Section 7 is welfare analysis and discusses optimal implementation of macro-prudential rule and monetary rule alongside fluctuations of business cycles; and Section 8 concludes.

3. The Model

3.1 The Economy

Two types of agents are analysed in the private sector: the household and firms. The household puts deposits in the wholesale bank, and firms use bank loans from the retail bank to finance its capital investment and labour payment. The household sells labour services and capital goods to the firms and purchases consumption goods from them. The firms buy labour services and capital goods from the household to produce consumption goods and sell consumption goods to the household. The consumption goods are non-durable and produce utility, and the capital goods – durable in nature - produce consumption goods as well as utility for the household.

Credit in the model economy is extended via the banking sector, which is set up to include the newly designed macro-prudential liquidity requirement NSFR. Two heterogeneous banks are assumed to facilitate the formulation of the model and adequately represent the transmission channel in the interbank market. The wholesale bank accepts deposits from the household, and extends interbank loans to the retail bank and purchases government bonds, while the retail bank extends corporate loans to the firms to facilitate payment for labour and capital investment. Note that the maturity of corporate loans is modelled as longer than one period and the maturity of the household deposits is modelled as one period, and the difference between these maturities is the maturity mismatch.

The fiscal authority issues government bonds for the household and the banks, and we move away from the fiscal authority's role in collecting taxation and deciding on public spending since our primary focus in this paper is default and maturity mismatch. The central bank conducts open market operations in the interbank market and implements monetary and macro-prudential rules. Unlike other agents, the fiscal authority and the central bank act as strategic dummies with no objective functions. A diagram of the economy's nominal flow is displayed as follows:

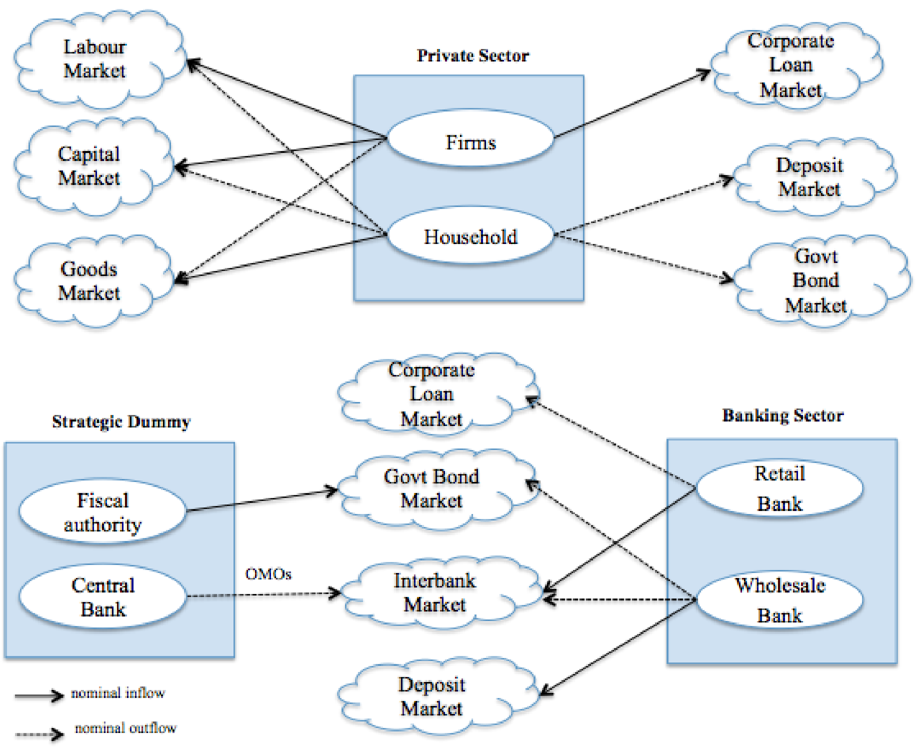

Figure1: Nominal flow in the benchmark economy

Formally, the notation that will be used henceforth is as follows:

$t \in \{0,1,2,3,\ldots\}$ = time periods,

$h \in \{\alpha, \theta\}$ = set of private sector agents (household/firms),

$fi \in \{w, r\}$ = set of banking sector agents(wholesale bank/retail bank),

$g \in \{FA, CB\}$ = strategic dummies(fiscal authority/central bank),

$e_t \in \{e_{n,t}, e_{k,t}\}$ = set of household endowments at t (labour, capital),

y_t= supply of total goods by the firm,

$X \in \{c_t\}$ = set of consumption demands (consumption goods),

$q \in \{q_t^n, q_t^k\}$ = set of factor endowment supply at t (labour/capital),

$b \in \{b_t^n, b_t^k\}$ = set of factor endowment demand at t (labour/capital),

$C_s \in \{D_t, W_t, L_t, l_t, \delta_t^r, M_t, B_t\}$ = set of credit supplies at t. They are the household deposit, supply of interbank loans, supply of total outstanding corporate loans, supply of newly issued corporate loans, supply of maturity of corporate loans[3], supply of base money, and supply of government bonds respectively.

[3] For lack of a better term, we use 'supply' and 'demand' of maturity of corporate loans, since

$C_d \in \{B_t^{\alpha}, u_t^{\theta}, \Delta u_t^{\theta}, \delta_t^{\theta}, B_t^{w}, u_t^{w}, B_t^{r}, u_t^{r}\}$ = set of credit demands at t. They are household demand for government bonds, firms' demand for total outstanding corporate loans, firms' demand for newly issued corporate loans, firms' demand for maturity of corporate loans, wholesale bank demand for government bonds, wholesale bank demand for household deposits, retail bank demand for government bonds and retail bank demand for interbank loans respectively.

$U(i,t)$ is the utility function of agent i, $U'(i,t) > 0$, $U''(i,t) \leq 0$; β_i is the discounting factor of agent i, and $i = \alpha, \theta, w, r$.

3.2 The Timing

As suggested by Tsomocos (2003), Goodhart et al. (2006), and Martinez and Tsomocos (2012), we model CIA constraints by dividing each period into two sub-periods, the beginning and the end of periods. At the beginning of each period, all uncertainties are resolved and transactions are settled in cash, and at the end of each period, trades take place against a backdrop of uncertainty regarding economic conditions, which will prevail at the beginning of the next period. Money introduced via CIA has two channels. One is the nominal channel through changing the inflation rate; the other one is a unique liquidity effect, because in this model setup, the central bank injects liquidity by providing high-powered money in the interbank market. Money injections initially affect only the balance sheet of the wholesale bank, a new channel by which real variables will be affected by monetary shocks. As long as the nominal interest rate is positive, the wholesale bank would want to increase its lending in response to a positive monetary injection. To induce the retail bank to borrow the additional funds, the wholesale bank would lower the interest rate on interbank loans, and in turn, the retail bank would lower the nominal interest rate on corporate loans, generating a liquidity effect. Since nominal interest rate influences household intertemporal consumption choices, such liquidity effect influences the real economy. Thus, in our DSGE model with no Calvo-style nominal rigidity, money

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these are choice variables of both the corporate bank and the firm. Detailed analysis is provided in the subsequent part.

supply is endogenised, and the liquidity effect from CIA is the main reason of the influence of money on real economic variables.

Since there is no Money-Utility-Function in this model and money is fiat, budgets constraints for all agents must be binding. Instead of holding idle cash, the individuals lend it to those who need it. Figure 2 exhibits the timeline of the model.

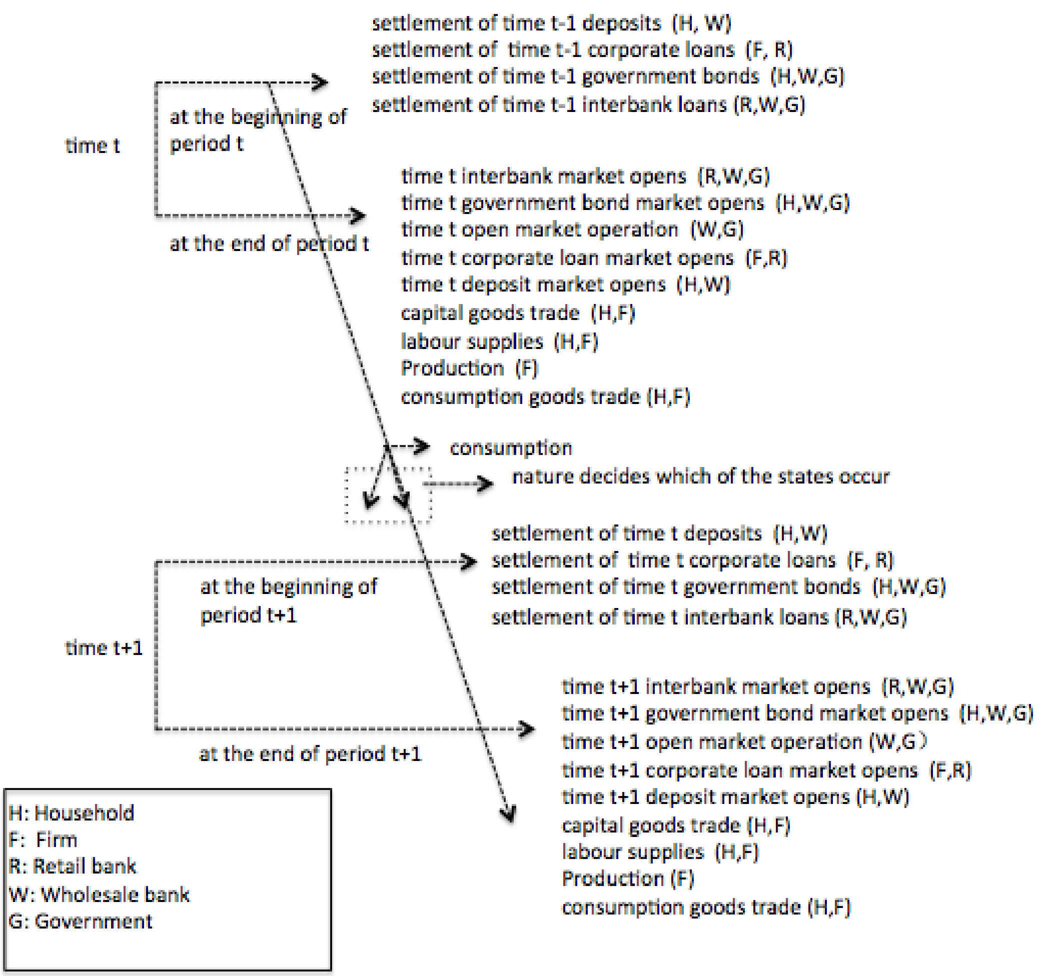

Figure 2: The time structure of the model

3.3 Default

One of the key topics of this paper is endogenous default of the firms and two heterogeneous banks. The household does not default because it is well endowed and has no borrowing, and the fiscal authority and the central bank do not default because they are modelled as strategic dummies. The agent i $(\mathrm{i} = \theta, \mathrm{w}, \mathrm{r})$ has an incentive to default on its borrowing because default would increase its profit and in turn increase its utility, but the agent borrows to an extent that the reputational or/and regulatory damage from default is bearable. We can rationalise reputational or/and regulatory damage as follows: if the agent i defaults repeatedly, then it would be more difficult for it to obtain credit in the future; because of CIA, it would also fail to operate normally, which would further hurt its utility. Additionally, if the agent is a bank, it would face surveillance from the regulatory authority that is promoting less government bailout and more bail-in of failing banks in the future, thus aggravating the non-pecuniary default penalty affecting the bank sector. So in our model, agent i can hurt its utility through default since we impose a non-pecuniary default penalty λ^{i}. Therefore, the agent chooses how much borrowing to default on and default is endogenised. Following the approach of Li Lin (2012) and Ahn and Tsomocos (2013), we used a quadratic form rather than a linear form to model non-pecuniary default penalty to avoid the case where the default penalty implies no variations in the borrowing agent's inter-temporal consumption, a situation that negates most of the dynamics. A detailed explanation of the choice of the function form of the default penalty is provided in Li Lin (2012).

3.4 Regulatory Tool (NSFR)

The macro-prudential tool NSFR requires the banks to hold more stable funding and fewer illiquid assets to reduce the maturity mismatch between the banks' assets and liabilities. A simplified formula[4] of NSFR is as follows:

$$NSFR = \frac{Available\ Amount\ of\ Stable\ Funding(ASF)}{Required\ Amount\ of\ Stable\ Funding(RSF)}$$

[4] The Basel III specification of NSFR is in the BCBS Consultative Document Basel III: The Net Stable Funding Ratio.

$$= \frac{Equity \times 100\% + Stable\ Funding \times 80\% + Unstable\ Funding \times 20\%}{Liquid\ Asset \times 20\% + Iliquid\ Asset \times 80\%}$$

The numerator is a weighted sum of various types of funding (borrowings and equity) of the banks, and generally the longer the maturity of the type of funding, the more weight is assigned. The denominator is a weighted sum of various types of assets, with assets of longer maturity bearing more weight. Additionally, safe assets are those that have near-zero default risks, such as government bonds, and are assigned more weight. Banks comply with the regulation by meeting the minimum NSFR requirement of 100%. This requirement would incentivise the banks to hold borrowings with longer maturities and invest in assets with shorter maturities or more safe assets. Typically, the maturity of corporate loans is longer than that of the household deposits. Implementing NSFR would reduce the maturity difference between corporate loans and household deposits, and help to dampen maturity mismatch. Additionally, it would also result in more safe assets held by the banks.

Therefore, implementing NSFR would manifest in two major aspects: 1) banks would hold more safe assets, such as government bonds whose default risk is zero in our model set-up; and 2) the average maturity of banks' assets would decrease, reducing maturity mismatch between the banks' assets and liabilities. Note that the other Basel III liquidity requirement LCR also results in the first manifestation, and in our analysis of NSFR policy implementation and its feedback rule, we focus mainly on the second manifestation.

To rationalise the first manifestation in our structural model, supposing that the wholesale bank and the retail bank invest in government debts, we impose a liquidity regulation that if the banks hold government debts, they need to hold them above a certain level; otherwise a non-pecuniary liquidity penalty z^w or z^r would hurt their utilities.

To rationalise the second manifestation, supposing that there is a continuum of identical firms indexed by $i \in [0,1]$. Each firm re-optimises a fraction $\tau_t (0 < \tau_t < 1)$ of capital in every period, but the firm can't adjust the rest of the fraction of the capital and has to keep this fraction $(1-\tau_t)$ at the previous level. In this way, we introduce a capital optimisation cycle $\frac{1}{\tau}$, so each firm's production cycle is greater than 1 period, and this rationalises the firm's need to apply for corporate loans that persist for longer than one period. Moreover, each firm can choose a proportion of total outstanding corporate loans to pay back in order to obtain new loans for the fraction of capital that is optimised in every period, we denote this proportion δ_t^{θ}, and its inverse $\frac{1}{\delta_t^{\theta}}$ is the average maturity of the corporate loans. Let r_t^l be the interest rate of the fraction of outstanding corporate loans that are not paid back. Then *ceteris paribus* δ_t^{θ} would increase with r_t^l, because as 'price' r^l increases, the firm would want to pay back more old loans. In other words, the average maturity of corporate loan, i.e. $\frac{1}{\delta_t^{\theta}}$, decreases with r_t^l. We call this relationship 'demand' for maturity mismatch, which is demonstrated by Figure 3[5].

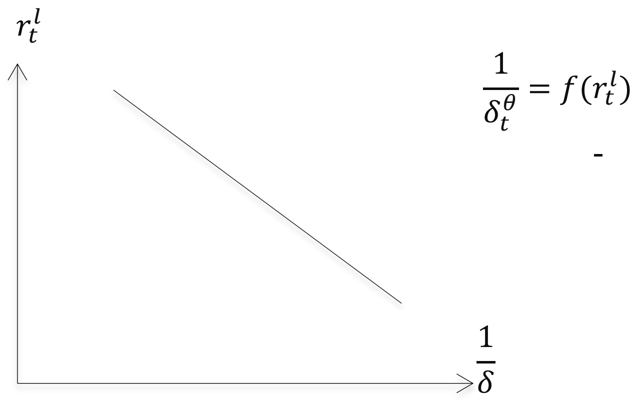

Figure 3: Demand for average maturity of corporate loans

In a general equilibrium framework, we also need to consider the 'supply' of average maturity of corporate loans. In other words, we need to analyse the retail bank, which supplies the firms with corporate loans. Suppose δ_t^r is the proportion of outstanding corporate loans that the retail bank would want the firms to pay back; then the inverse of

[5] This figure is illustrative only. The exact function form between r_t^l and $\frac{1}{\delta_t^{\theta}}$ can only be examined through the equilibrium solutions.

δ_t^r, i.e. $\frac{1}{\delta_t^r}$, is the average maturity of the corporate loans chosen by the retail bank. When the interest rate (r_t^l) on the corporate loan increases, δ_t^r decreases, because the retail bank would want less outstanding loans to be paid back so that interest payment from the firms would go up; this allows an increase in profit that causes corporate loan maturity to rise and the maturity mismatch becomes more severe. So the average maturity of corporate loans chosen by the retail bank, i.e. $\frac{1}{\delta_t^r}$, increases with r_t^l. For lack of a more suitable term, we call this relation 'supply' of corporate loan maturity, as demonstrated in Figure 4[6]. Usually, the supply curve is very elastic because the retail bank can borrow from a very liquid interbank market. However, the choice of corporate loan maturity does not affect its flow of fund constraint, supporting the likelihood of a flatter supply curve.

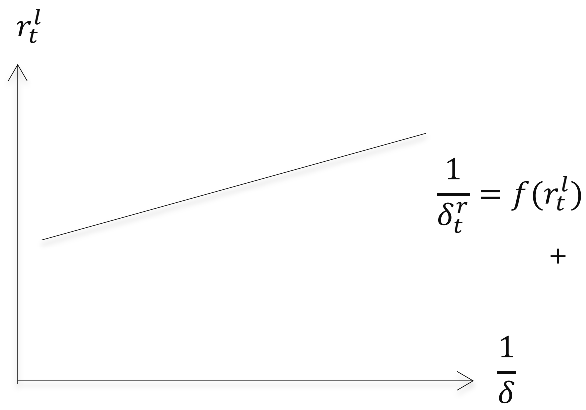

Figure 4: 'Supply' of corporate loan maturity

The combination of Figures 3 and 5 allows us to illustrate the equilibrium of corporate loan maturity, i.e. $\frac{1}{\delta_t^*}$ in Figure 6. To rationalise NSFR, we impose the requirement that the retail bank has to choose δ_t^r above a certain level, δ, to reduce the average maturity of corporate loans; otherwise, a non-pecuniary regulatory penalty ψ would hurt the retail bank's utility. When NSFR is implemented, the non-pecuniary regulatory punishment for maturity mismatch becomes heavier, *ceteris paribus*, so δ increases, shifting the 'supply

[6] This figure is illustrative only. The exact function form between r_t^l and $\frac{1}{\delta_t^r}$ can only be examined through the equilibrium solutions.

curve' of maturity to the left and pushing down the equilibrium level of corporate loan maturity to $\frac{1}{\delta_t^{*\prime}}$. This sequence results in maturity mismatch becoming less severe, and the process is illustrated in Figure 5.

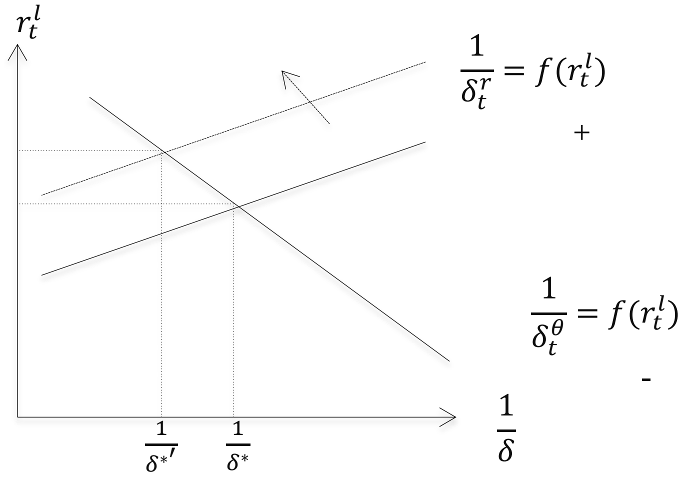

Figure 5: Equilibrium of corporate loan maturity

3.5 Model Set-up

3.51 Private Sector

Household (α)

The household derives utility from consuming goods (c_t) and holding capital goods and having leisure. According to standard practice in real business cycle literature, we assume that the household is risk-averse and maximises the discounted sum of lifetime utility. Every period the household is rich in capital endowment ($e_{k,t}$) and labour endowment ($e_{n,t}$). It sells part of its capital endowment q_t^k at the price of p_t^k and supplies labour q_t^n at the price of p_t^n to the firms. It relies on investing in government bonds B_t^α and making deposits D_t into the wholesale bank for consumption smoothing because government bonds and deposits would bring interest payment r_t^b and r_t^d respectively.

As the household is endowed with labour, capital and money every period, it's not a borrowing agent. More specifically:

$$\underbrace{\max}_{c_t, q_t^n, q_t^k, D_t, B_t^\alpha} \quad E_0 \Sigma_{t=0}^{\infty} \beta_\alpha^t U(\alpha, t) \tag{3.1}$$

$$\text{Where } U(\alpha, t) = \mathcal{X}_c \ln c_t + \mathcal{X}_k \ln k_t^\alpha + \mathcal{X}_n \ln(e_{n,t} - q_{n,t}) \tag{3.2}$$

Subject to

$$D_t + B_t^\alpha + c_t \leq \frac{R_t^w(1+r_{d,t-1})D_{t-1}}{\pi_t} + \frac{(r_{b,t-1}+1)B_{t-1}^\alpha}{\pi_t} + \frac{p_{n,t-1}q_{n,t-1}}{\pi_t} + \frac{p_{k,t-1}q_{k,t-1}}{\pi_t} + \Sigma_{i\epsilon(\theta,w,r)}\Omega_t^i \tag{3.3}$$

$$k_t^\alpha = (1-d)k_{t-1}^\alpha + e_{k,t} - q_{k,t} \tag{3.4}$$

Note that R_t^w is the wholesale bank's repayment rate of household deposits expected by the household. Under rational expectation, it would equal the actual wholesale bank's repayment rate. Ω^i is the profit share from the firms or the banks.

Equation (3.3) summarizes all of household's transactions. The right hand side summarises all income sources. At the beginning of t, the household receives sales income from selling capital goods and labour service at t-1, and it also retains income from its asset investments in deposits and government bonds. Additionally, the household receives profit shares from the firm and banks. The left hand side is the use of income. At the end of t, the household uses the income to purchase private goods, makes deposits into the wholesale bank and buys government bonds. We adjust last period's variables by an inflation deflator. Equation (3.4) is the household's capital accumulation law, similar that of the firm. Physical capital depreciates at the rate of d and the household refills its capital by $\mathrm{e_{k,t}} - \mathrm{q_{k,t}}$ in every period.

The household is modelled as rich in every period because it has an endowment in labour and capital, whose log-linearised forms are modelled as AR (1) processes in (3.5) and (3.6). We assume that the long-run endowments of labour and capital are constants, i.e. $\overline{\mathrm{e_n}}$ and $\overline{\mathrm{e_k}}$.

$$\ln e_{n,t} = \rho_n \ln e_{n,t-1} + (1-\rho_n)\ln\overline{e_n} + \epsilon_{n,t} \tag{3.5}$$

$$\epsilon_{n,t} \sim i.i.d.N(0, \sigma_n^2)$$

$$\ln e_{k,t} = \rho_k \ln e_{k,t-1} + (1 - \rho_k)\ln\overline{e_k} + \epsilon_{k,t} \tag{3.6}$$

$$\epsilon_{k,t} \sim i.i.d.N(0, \sigma_k^2)$$

where ρ_k and ρ_n are the AR (1) coefficients, and σ_n and σ_k represent the standard deviations of endowment shocks.

Firms (θ)

We assume there is a continuum of firms $i \epsilon$ [0,1] and each firm is homogenous in terms of maximisation behaviour, resource constraints and the probability of re-optimising capital. We use θ to denote aggregate variables of the firm.

At the beginning of each period, each firm makes a profit, which is calculated as the difference between the sales income carried forward from the previous period and the amount it has to pay on its liabilities from previous periods adjusted for its repayment rate. Note that each firm can choose to pay back only a proportion of its previous outstanding loans and postpone the repayment of the rest of the loans to the future, so that the firm can choose to extend the maturity of the loans for longer than one period. At the end of this period, the expenditure of the firm, which consists of wage payment and capital investment, must be equal to or less than its liabilities obtained from the corporate loan market, i.e. from the retail bank.

Production is the standard Cobb-Douglas production and capital investment accumulates according to the standard law of motion. Each firm produces consumption goods and sells it to the household. Each firm derives utility from profit and incurs utility loss from default on its loans.

To rationalise each firm's inherent need for loans with maturity longer than one period, we now depart from the typical RBC setup and assume that each firm re-optimises a fraction $\tau_t (0 < \tau_t < 1)$ of capital in every period, but the firm can not adjust the rest of the fraction of the capital and has to keep this fraction $(1 - \tau_t)$ at the previous level. One way to rationalise our restriction on the firm's infrequent adjustment of the capital is as follows. It usually involves some fixed costs for a firm to purchase a new machine or to build a new plant, as assumed in the literature (Thomas 2002, Khan and Thomas 2003, among others). These fixed costs come from gathering information, training new workforce, decision making, etc. and imply that the firm makes lumpy investment (Hammermesh and Pfann 1996, Cooper and Haltiwanger 2006). Our setup does not attempt to model the exact nature of firm's infrequent adjustment of capital and capital-adjustment cost, but it still captures the macroeconomic implications of firm's capital reoptimisation process. This specification of lumpy investments, or infrequent capital adjustment, has been previously adopted by Kiyotaki and Moore (1997) and Sveen and Weinke (2007) in the context of firm-specific capital, but we depart from their setup by assuming homogeneous capital across firms, a competitive rental market and homogenous firms. In this manner, we have introduced a capital-optimisation cycle $\frac{1}{\tau}$, thus, the firm's production cycle is greater than one period. Martin Andreasen et al (2012) provide a more detailed explanation for this assumption. Therefore, overall, the firm's inherent need for loan maturity ($\frac{1}{\delta_t}$) is longer than one period ($1 < \frac{1}{\delta_t} < \frac{1}{\tau_t}$)[7].

Since each firm (i) is representative, we drop the subscript (i) and look at the aggregate case in the setup below.

$$\underbrace{max}_{b^\theta_{k,t}, b^\theta_{n,t}, v^\theta_t, \Delta u^\theta_t, \delta^\theta_t} \quad \Sigma^{\infty}_{t=0} \beta^t_\theta U(\theta, t) \tag{3.7}$$

$$U(\theta, t) = \Omega^\theta_t - \frac{\lambda_\theta}{2}\left[\frac{(1-v^\theta_t)\delta^\theta_t u^\theta_{t-1}(1+r_{l',t-1})}{\pi_t}\right]^2 \tag{3.8}$$

Subject to

At the beginning of period t:

$$\Omega^\theta_t = \frac{1}{\pi_t}\{y_{t-1} - [(1-\delta^\theta_t)u^\theta_{t-1}r_{l,t-1} + (1-\delta^\theta_t)u^\theta_{t-1} + v^\theta_t u^\theta_{t-1}\delta^\theta_t(1+r_{l',t-1})]\} \tag{3.9}$$

[7] Because each firm re-optimises with respect to labour each period, the average maturity of corporate loans should be shorter than capital optimisation cycle.

At the end of period t:

$$p_{n,t}b_{n,t} + \tau_t p_{k,t}b_{k,t} \le \Delta u_t^{\theta} \tag{3.10}$$

$$(1-\tau_t)p_{k,t}b_{k,t-1} \le \left(1-\delta_t^{\theta}\right)u_{t-1}^{\theta} \tag{3.11}$$

$$y_t = \alpha_t\left(k_{t-1}^{\theta}\right)^c b_{n,t}^{1-c} \tag{3.12}$$

$$k_t^{\theta} = (1-d')k_{t-1}^{\theta} + \tau_t b_{k,t} + (1-\tau_t)b_{k,t-1} \tag{3.13}$$

$$u_t^{\theta} = \left(1-\delta_t^{\theta}\right)u_{t-1}^{\theta} + \Delta u_t^{\theta} \tag{3.14}$$

Note that v_t^{θ} is the repayment rate of corporate loans, and $(1-v_t^{\theta})$ is the default rate of corporate loans. Moreover, there are two prices for the corporate loans: $r_{l,t}$ is the interest payment on outstanding loans that have not been paid back for capital-optimisation at this period, and $r_{l',t}$ is the interest payment on the proportion of outstanding loans that are paid back for capital-optimisation at this period. The two prices function to accommodate the two markets regarding corporate loans: the corporate loan market and the 'market' for corporate loan maturity.

Equation (3.9) is CIA; it is also the profit, which equals previous period's revenue minus any outstanding dues to the retail bank. The first term of (3.9) is the total revenue realised at the beginning of period t from selling the products produced at period t-1, the second term is the interest payment incurred on the fraction of the last period corporate loans that are not paid back at the beginning of this period, the third term is the fraction of the last period corporate loans which are not paid back, but are used to support the fraction of the capital demand that's not re-optimised this period (shown by (3.11), and forth term is the repayment of the fraction of the last period corporate loans that are paid back along with the interest incurred.

Condition (3.10) is the new borrowing from the retail bank to finance re-optimised capital investment and wage at the end of the period. Note that the capital investment backed by the new corporate loans should be $\tau_t p_{k,t}b_{k,t}$ rather than $p_{k,t}b_{k,t}$ because only a fraction τ_t of capital is re-optimised. The other fraction $1-\tau_t$ is maintained as previous level and is backed by last period loans that haven't been paid back, as captured in Condition (3.11).

Equation (3.12) is the Cobb-Douglas production function, where c and $1-c$ are the output elasticities of capital stock and labour services respectively. And we assume the log-linearised form of the productivity factor α_t follows a simple AR (1) process:

$$\ln\alpha_t = \rho_\alpha \ln\alpha_{t-1} + (1-\rho_\alpha)\ln\bar{\alpha} + \epsilon_{a,t} \tag{3.15}$$

Equation (3.12) may not seem obvious because it implies

$$\int_0^1 a_t\left(k_{it-1}^\theta\right)^c b_{in,t}^{1-c} di = a_t\left(k_{t-1}^\theta\right)^c b_{n,t}^{1-c}$$

However, it follows the notion that firms are identical and can be thought of as a representative firm. For individual firm i, the first-order condition[8] for the labour is

$$b_{in,t} = E_t\left(\frac{\eta_t^\theta p_{n,1}\pi_{t+1}}{\beta_\theta a_t(1-c)}\right)^{-\frac{1}{c}} k_{it-1}^\theta \tag{3.16}$$

In equilibrium, the aggregate demand of capital holding must equal the capital holding demand of all firms.

$$k_{t-1}^\theta = \int_0^1 k_{it-1}^\theta di \tag{3.17}$$

Market clearing in the labour market implies that

$$b_{n,t} = \int_0^1 b_{in,t} di \tag{3.18}$$

Substitute (3.16) into (3.18) and we get,

$$b_{n,t} = \int_0^1 E_t\left(\frac{\eta_t^\theta p_{n,1}\pi_{t+1}}{\beta_\theta a_t(1-c)}\right)^{-\frac{1}{c}} k_{it-1}^\theta di$$

$$b_{n,t} = E_t\left(\frac{\eta_t^\theta p_{n,1}\pi_{t+1}}{\beta_\theta a_t(1-c)}\right)^{-\frac{1}{c}} \int_0^1 k_{it-1}^\theta di = E_t\left(\frac{\eta_t^\theta p_{n,1}\pi_{t+1}}{\beta_\theta a_t(1-c)}\right)^{-\frac{1}{c}} k_{t-1}^\theta \tag{3.19}$$

From (3.16) and (3.19), we get

$$\frac{k_{it-1}^\theta}{b_{in,t}} = \frac{k_{t-1}^\theta}{b_{n,t}} \tag{3.20}$$

Because $y_t = \int_0^1 y_{it} di = \int_0^1 a_t\left(k_{it-1}^\theta\right)^c b_{in,t}^{1-c} di = \int_0^1 a_t\left(\frac{k_{it-1}^\theta}{b_{in,t}}\right)^c b_{in,t} di$ (3.21)

Substitute (3.20) into (3.21),

$$y_t = \int_0^1 y_{it} di = \int_0^1 a_t\left(k_{it-1}^\theta\right)^c b_{in,t}^{1-c} di = \int_0^1 a_t\left(\frac{k_{it-1}^\theta}{b_{in,t}}\right)^c b_{in,t} di = a_t\left(\frac{k_{t-1}^\theta}{b_{n,t}}\right)^c \int_0^1 b_{in,t} di =$$

[8] See Section A of the Appendix

$\alpha_t\left(k_{t-1}^{\theta}\right)^c b_{n,t}^{1-c}$ QED.

Equation (3.13) is the law of motion of capital stock accumulation. Capital depreciates at the rate of d' at every period and the firm refills its capital stock by $\tau_t b_{k,t} + (1 - \tau_t)b_{k,t-1}$ at every period through new capital investment. Note that each firm re-optimises a fraction $\tau_t (0 < \tau_t < 1)$ of capital in every period, but the firm can't adjust the rest of the fraction of the capital and has to keep this fraction $(1 - \tau_t)$ at the previous level. From (3.12), the production at period t uses accumulated capital at period $t - 1$, because the production should happen before period t's capital accumulation, which finishes at the very end of this period.

Equation (3.14) encapsulates the loan dynamics. At period t, only a proportion of previous outstanding loans are paid back. The total outstanding loans demanded at period t equals the proportion of total outstanding loans at period t-1 that has not been paid back plus the new loans demanded by the firm at period t.

Incidentally, (3.10) (3.11) and (3.14) can be combined as

$$p_{n,t}b_{n,t} + p_{k,t}[\tau_t b_{k,t} + (1 - \tau_t)b_{k,t-1}] \leq u_t^{\theta} \tag{3.22}$$

And the maximisation problem with respect to Δu_t^{θ} is equivalent to the maximisation problem with respect to u_t^{θ}. Appendix A shows that with some manipulation, the first order conditions with respect to (3.10) (3.11) and (3.14) are identical to the first order conditions with respect to (3.11) and (3.22).

The optimality conditions with respect to labour demand, capital demand, corporate-loan demand, corporate-loan maturity demand and repayment rate choice are ordinally presented with the following equations. The impact of default and the decision on the corporate loan maturity are reflected in the first-order-conditions.

$$\frac{\partial L(\theta,t)}{\partial b_{n,t}}: E_t\beta_\theta\left(\frac{a_t\left(k_{t-1}^\theta\right)^c(1-c)\left(b_{n,t}\right)^{-c}}{\pi_{t+1}}\right)=\eta_t^\theta p_{n,t} \tag{3.23}$$

$$\frac{\partial L(\theta,t)}{\partial b_{k,t}}: E_t\beta_\theta^2\left(\frac{a_{t+1}c(k_t^\theta)^{c-1}b_{n,t+1}^{1-c}}{\pi_{t+2}}\right)\tau+E_t\beta_\theta^3\left(\frac{a_{t+2}c\left(k_{t+1}^\theta\right)^{c-1}b_{n,t+2}^{1-c}}{\pi_{t+3}}\right)(1-\tau)=\eta_t^\theta\tau p_{k,t}+ E_t\beta^\theta\left(\eta_{t+1}+\eta_{t+1}^\theta\right)p_{k,t+1}(1-\tau)-E_t\beta_\theta(1-d)\eta_{t+1}^\theta\tau p_{k,t+1}-E_t\beta_\theta^2(1-d)\left(\eta_{t+2}+\eta_{t+2}^\theta\right)p_{k,t+2}(1-\tau) \tag{3.24}$$

$$\frac{\partial L(\theta,t)}{\partial u_t^\theta}: \eta_t^\theta+E_t\beta_\theta\eta_{t+1}\left(1-\delta_{t+1}^\theta\right)=E_t\beta_\theta\left[\frac{\left(1-\delta_{t+1}^\theta\right)(r_{l,t}+1)}{\pi_{t+1}}+\frac{\delta_{t+1}^\theta\left(1+r_{l',t}\right)}{\pi_{t+1}}\right] \tag{3.25}$$

$$\frac{\partial L(\theta,t)}{\partial \delta_t^\theta}: \frac{r_{l,t-1}+1}{\pi_t}=\eta_t+\frac{\left(1+r_{l',t-1}\right)}{\pi_t} \tag{3.26}$$

$$\frac{\partial L(\theta,t)}{\partial v_t^\theta}: \frac{\lambda_\theta(\delta_t^\theta)^2(u_{t-1}^\theta)^2(1+r_{l',t-1})^2(1-v_t^\theta)}{\pi_t^2}=\frac{u_{t-1}^\theta\delta_t^\theta(1+r_{l',t-1})}{\pi_t} \tag{3.27}$$

Conditions (3.23) and (3.24) relate to the firm's decision on labour and capital demand. Using (3.24) as an example: the firm buys one more unit of capital, as a result, the tightened flow of fund constraint (3.10) and (3.11) lowers the firm's utility by $\eta_t^\theta\tau p_{k,t}+E_t\beta^\theta\left(\eta_{t+1}+\eta_{t+1}^\theta\right)p_{k,t+1}(1-\tau)$. η_t^θ and η_t are the shadow prices corresponding to (3.10) and (3.11) respectively. According to the law of motion (3.13), one more unit of capital this period means less demand for capital next period, and the flow of fund constraints (3.10) and (3.11) in the following period are consequentially relaxed, increasing the firm's utility by $E_t\beta_\theta(1-d)\eta_{t+1}^\theta\tau p_{k,t+1}+E_t\beta_\theta^2(1-d)\left(\eta_{t+2}+\eta_{t+2}^\theta\right)p_{k,t+2}(1-\tau)$. Moreover, the increased amount of capital raises the firm's utility by $E_t\beta_\theta^2\left(\frac{a_{t+1}c(k_t^\theta)^{c-1}b_{n,t+1}^{1-c}}{\pi_{t+2}}\right)\tau+E_t\beta_\theta^3\left(\frac{a_{t+2}c\left(k_{t+1}^\theta\right)^{c-1}b_{n,t+2}^{1-c}}{\pi_{t+3}}\right)(1-\tau)$, since more capital enters the production function and generates more revenue.

Conditions (3.25) and (3.26) capture the firm's financing decisions. Take condition (3.25) for example, when the firm increases one unit of borrowing of corporate loans, the flow of fund constraints (3.22) and (3.11) are relaxed, increasing the firm's utility by $\eta_t^\theta+E_t\eta_t\left(1-\delta_{t+1}^\theta\right)$. Moreover, an increase in corporate loans means more repayment in the future, lowering the firm's utility by $E_t\beta_\theta\left[\frac{\left(1-\delta_{t+1}^\theta\right)r_{l,t}}{\pi_{t+1}}+\frac{\delta_{t+1}^\theta\left(1+r_{l',t}\right)}{\pi_{t+1}}\right]$. (3.26) is the firm's decision on the maturity of loans $\frac{1}{\delta_t^\theta}$. An increase in the maturity of loans increases the firm's utility by $\frac{(1+r_{l',t-1})}{\pi_t}$, since the firm postpones repayment, and also results in an increase in loan maturity relaxes (3.11), the benefit is η_t ; on the other hand, an increase in the maturity of corporate loans increases the firm's utility by $\frac{r_{l,t-1}+1}{\pi_t}$. Note that in (3.26), the higher the interest rate $(r_{l,t-1})$ on long-maturity corporate loan is, the more costly it is to extend for longer maturity. This relationship was illustrated earlier in Figure 3.

Condition (3.27) is the firm's decision on repayment rate. By repaying one unit less, the firm retains more profit, increasing utility by $\frac{u_{t-1}^{\theta}\delta_t^{\theta}(1+r_{l',t-1})}{\pi_t}$; consequently, the firm suffers in reputation cost due to default, lowering utility by $\frac{\lambda_\theta(\delta_t^{\theta})^2(u_{t-1}^{\theta})^2(1+r_{l',t-1})^2(1-v_t^{\theta})}{\pi_t}$.

3.52 Banking Sector

Wholesale Bank (w)

The wholesale bank takes household deposits and invests in government bonds and interbank loans that are extended to the retail bank. The following table is a simplified balance sheet of the wholesale bank.

Table 1: Wholesale bank balance sheet

Asset	Liability
Gov. bonds B_t^w	Deposits from the household D_t
Interbank loans W_t	

At the end of each period, when the wholesale bank uses household deposits to invest in government bonds B_t^w and interbank loans W_t, it extends interbank loans to the retail bank, which in turns extends corporate loans to the firm.

The dynamic optimisation process of the wholesale bank is formalised as follows:

$$\underbrace{max}_{B_t^w, W_t, v_t^w, u_t^w} \quad \Sigma_{t=0}^{\infty} \beta_w^t U(w,t) \tag{3.28}$$

$$U(w,t) = \frac{(\Omega_t^w)^{1-\sigma^w}}{1-\sigma^w} - \frac{\lambda_w}{2}\left[\frac{(1-v_t^w)u_{t-1}^w(1+r_{d,t-1})}{\pi_t}\right]^2 - z^w(B_t^w + W_t)\cdot \max(0, c^w - c_t^w) \tag{3.29}$$

Subject to

At the beginning of t:

$$\Omega_t^w = \frac{1}{\pi_t}[(1+r_{b,t-1})B_{t-1}^w + W_{t-1}(1+r_{il,t-1})R_t^r - v_t^w(1+r_{d,t-1})u_{t-1}^w] \tag{3.30}$$

At the end of t:

$$B_t^w + W_t \leq u_t^w \tag{3.31}$$

$$c_t^w = \frac{B_t^w}{B_t^w + W_t} \tag{3.32}$$

Note that v_t^w is the repayment rate of the wholesale bank on its liabilities. The default rate on its liabilities is $1 - v_t^w$. R_t^r is the expected repayment rate of the retail bank, which would equal to the actual repayment rate of the retail bank based on rational expectation. c is the regulatory ratio of safe assets to total assets, reflecting the scenario that NSFR encourages banks to hold more safe assets, i.e. government bonds. $r_{il,t}$ is the nominal interest rate of interbank loans. σ^w is the risk-aversion parameter of the wholesale bank.

From Equation (3.29), the wholesale bank derives utility from making profits. The second term in the utility function represents the non-pecuniary default punishment and the third term represents the regulatory punishment for holding excessive illiquid assets, a manifestation of the Basel III structural liquidity requirement Net Stable Funding Ratio (NSFR), which encourages banks to hold more safe assets.

Equation (3.30) is the CIA, which summarizes the profit from operation at period t-1; this realises at the beginning of period t. The profit equals the difference between what it receives from extending interbank loans and holding government bonds and what it repays on its liabilities, adjusted for repayment rates.

Condition (3.31) is the budget constraint which demands for the wholesale bank's credit extensions to be be less than or equal to its liabilities at the very end of period t.

Equation (3.32) is the ratio of safe assets (government bonds) to total assets, and a regulatory cost will incur if this ratio deviates from the safe assets to total assets ratio set by the regulatory authority. Note that the safe assets to total assets ratio set by the regulatory authority is one manifestation of NSFR, which encourages banks to hold more safe assets.

The optimality conditions of the wholesale bank are specified in Section A of the Appendix, and can be interpreted in a similar fashion as the firm's optimality conditions.

Retail Bank (r)

The retail bank borrows from interbank market, invests in government bonds and extends corporate loans to the firm. Table 2 is a snapshot of the balance sheet of the retail bank.

Table 2: Simplified balance sheet of the retail bank

Asset	Liability
Gov bonds B_t^r	Borrowing from interbank market u_t^r
Loans to the firm L_t^r	

More specifically,

$$\underbrace{max}_{l_t, v_t^r, \delta_t^r, u_t^r} \quad \Sigma_{t=0}^{\infty} \beta_r^t U(r,t) \tag{3.33}$$

$$U(r;t) = \frac{(\Omega_t^r)^{1-\sigma^r}}{1-\sigma^r} - \frac{\lambda_r}{2}\left[\frac{(1-v_t^r)u_{t-1}^r\left(1+r_{il,t-1}\right)}{\pi_t}\right]^2 -$$

$$\psi L_{t-1} \cdot \max\left(0, (\delta_t - \delta_t^r)\right) - z^r(B_t^r + L_t)\max(0, (c^r - c_t^r)) \tag{3.34}$$

Subject to

At the beginning of period t:

$$\Omega_t^r = \frac{1}{\pi_t}[\left(1+r_{b,t-1}\right)B_{t-1}^r + (1-\delta_t^r)L_{t-1}(r_{l,t-1}+1) + R_t^\theta L_{t-1}\delta_t^r\left(1+r_{l',t-1}\right) -$$

$$v_t^r u_{t-1}^r\left(1+r_{il,t-1}\right)] \tag{3.35}$$

At the end of period t:

$$B_r + (1-\delta_t^r)L_{t-1} + l_t \leq u_t^r \tag{3.36}$$

$$\text{Where } L_t = (1-\delta_t^r)L_{t-1} + l_t \tag{3.37}$$

$$c_t^r = \frac{B_t^r}{B_t^r + L_t} \tag{3.38}$$

Note that v_t^r is the repayment rate of the retail bank on its borrowing from the interbank market. So the default rate of the retail bank on its borrowing is $1 - v_t^r$. R_t^θ is the expected repayment rate of the firms, which would equal the actual repayment rate of the firms based on the retail bank's rational expectations. σ^r is the risk-aversion parameter of the retail bank.

From (3.34), the retail bank derives utility from making profit, and its utility is hurt by the penalty of its default on its borrowing and the level of maturity mismatch it chooses. Note that the key manifestation of NSFR is the parameter δ_t, the higher it is, then the more costly it is for the retail bank to fall short of its NSFR requirement. To study how macro-prudential policy, such as NSFR, can affect the economy, we assume a simple feedback rule for the desired level of maturity mismatch $\frac{1}{\delta_t}$. $1-\omega$ is the backward-looking parameter, ω is the feedback rule coefficient on output growth, and δ is the steady-state value for the macro-prudential instrument.

$$\delta_t = \delta_{t-1}^{1-\omega}\delta\left(\frac{y_t}{y}\right)^{\omega} e^{\epsilon_{\delta,t}} \text{ Where } \epsilon_{\delta,t} \sim i.i.d.N(0,\sigma_\delta^2) \tag{3.39}$$

Equation (3.35) is the CIA, which summaries the retail bank's profit settled at the beginning of every period. This profit is the difference between what it receives from investing in government bonds and extending loans to firms and its payout towards loans its borrowing from the interbank market, adjusted for repayment rates. Noteworthy is the second term $(1-\delta_t^r)L_{t-1}(r_{l,t-1}+1)$, because if δ_t^r is the fraction of last period loans that the retail bank wants the firms to pay back, then it may seem that the second term should just be $(1-\delta_t^r)L_{t-1}r_{l,t-1}$, since it seems that the retail bank only gain interest rate from the fraction of the loans that are not paid back. Nevertheless, the retail bank should gain $(1-\delta_t^r)L_{t-1}$ as well, because the firms could have returned $\left(1-\delta^\theta\right)u_{t-1}^\theta$ to the bank and reborrowed the same amount to finance the fraction of loans that are not re-optimised, but the firms use $\left(1-\delta^\theta\right)u_{t-1}^\theta$ to finance the fraction of non-reoptimised loans directly, and this means an indirect gain in retail bank's profit.

Condition (3.36) says that at the end of the period, the retail bank's credit extension and investment in government bonds should be equal to or smaller than its borrowing from the interbank market.

Equation (3.37) is the corporate loan dynamics on the supply side. The total outstanding loans supplied by the retail bank should be equal to the total outstanding loans supplied by the retail bank at previous periods that have not been paid back plus the new corporate loans supplied by the retail bank during this period.

Note that condition (3.36) and equation (3.37) can be combined as

$$B_r + L_t \leq u_t^r \tag{3.40}$$

As shown in Section A of the Appendix, the separate constraints and the combined constraint yield the same first-order optimality conditions.

Equation (3.38) is the ratio of safe assets (government bonds) to the total assets; a regulatory cost will incur if this ratio deviates from the safe assets to total assets ratio set by the regulatory authority. Note that the safe assets to total assets ratio set by the regulatory authority is one manifestation of NSFR, which encourages banks to hold more safe assets.

The optimality conditions can be interpreted in a similar fashion to the firm's optimality conditions. To demonstrate, we shall look at the conditions with respect to corporate loan extension and corporate loan maturity.

$$\frac{\partial L(r,t)}{\partial L_t}: E_t\beta_r\left[\frac{(1-\delta_{t+1}^r)(r_{l,t}+1)+R_{t+1}^{\theta}\delta_{t+1}^r\left(1+r_{l',t}\right)}{\pi_{t+1}(\Omega_t^r)^{\sigma^r}}\right]=\eta_t^r+z^r c^r+E_t\beta_r\psi(\delta_{t+1}-\delta_{t+1}^r) \tag{3.41}$$

$$\frac{\partial L(r,t)}{\partial \delta_t^r}: \left[-(r_{l,t-1}+1)+R_t^{\theta}\left(1+r_{l',t-1}\right)\right]\frac{(\Omega_t^r)^{-\sigma^r}}{\pi_t}+\psi=0 \tag{3.42}$$

Condition (3.41) relates to the retail bank's decision to extend corporate loans to the firm. When extending one more unit of corporate loans, the retail bank's flow of fund constraint (3.40) is tightened, which lowers the retail bank's utility by η_t^r. Meanwhile extending more corporate loans hurts the retail bank's liquidity ratio (3.38), and lowers its utility by $z^r c^r$. Also extending more corporate loans amplifies the non-pecuniary penalty cost of maturity mismatch, lowering the retail bank's utility by $E_t\beta_r\psi(\delta_t-\delta_{t+1}^r)$. On the other hand, extending one more unit of corporate loans this period brings return in the next period, increasing the utility by $E_t\beta_r\frac{(1-\delta_{t+1}^r)(r_{l,t}+1)+R_{t+1}^{\theta}\delta_{t+1}^r\left(1+r_{l',t}\right)}{\pi_{t+1}(\Omega_t^r)^{\sigma^r}}$.

Condition (3.42) relates the retail bank's decision to extend corporate loan maturity ($\frac{1}{\delta_t^r}$). Note that the supply curve of corporate loan maturity is very elastic, and the 'price' $r_{l,t}$ is only decided by the regulatory parameter ψ; this is because the interbank market is very liquid, the corporate loan maturity $\frac{1}{\delta_r^r}$ has no influence on the retail bank's flow of funds, unlike the case with firms. Therefore the 'supply curve' of corporate loan maturity in Figure 4 should be

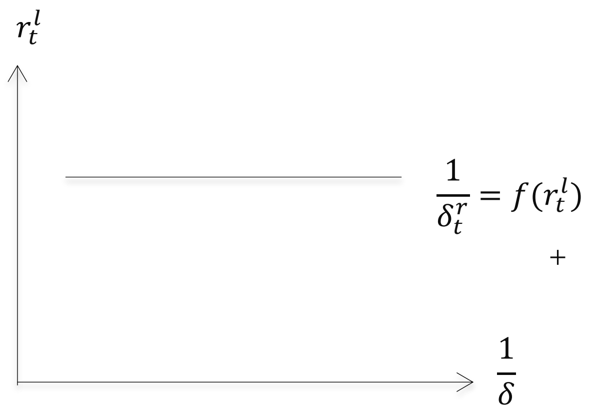

Figure 6: 'Supply' of corporate loan maturity

The dynamics of how the market clears for corporate loan maturity is demonstrated in Figure 7. The up-shift of the supply curve is due to a more stringent regulation for maturity mismatch, i.e. ψ increases, and a decrease in corporate loan maturity is reflected in the shift from $\frac{1}{\delta^*}$ to $\frac{1}{\delta^{*\prime}}$.

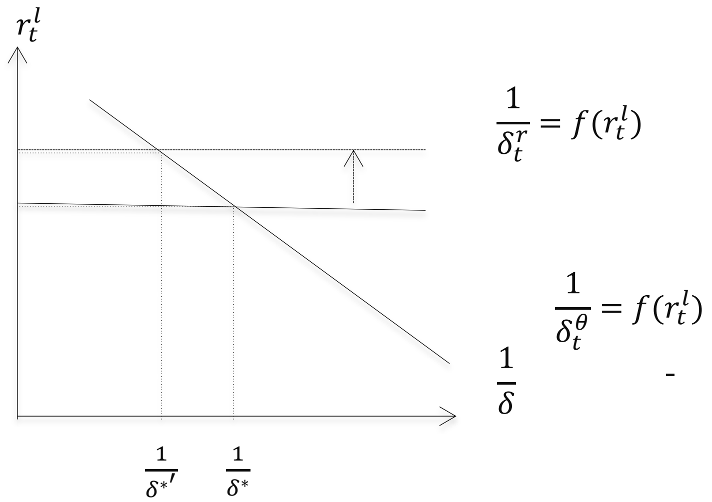

Figure 7: Equilibrium of corporate loan maturity

3.53 Public Sector

Central Bank

The central bank is modelled as a strategic dummy, and sets the minimal interest rate $r_{il,t}$ in the interbank market following a Taylor rule as in (3.43). ζ is a backward-looking parameter, r_{il} is the steady-state value of interbank rate.

$$r_{il,t} = r_{il,t-1}^{\zeta}\left[r_{il}\left(\frac{\pi_t}{\pi}\right)^{\rho_\pi}\left(\frac{y_t}{y_{t-1}}\right)^{\rho_y}\right]^{1-\zeta} e^{\epsilon_{r,t}} \text{ Where } \epsilon_{r,t} \sim i.i.d. N(0, \sigma_r^2) \tag{3.43}$$

As the central bank controls the money supply through compliance with the Taylor rule, the central bank the central bank provides loans M_t in the interbank market to meet the demand and target interest rate $r_{il,t}$ at period t. In this process, the central bank makes profits or losses (seiniorage) S_t, which goes to the fiscal authority.

$$S_t = \frac{M_{t-1}}{\pi_t}\left[R_t^r\left(1 + r_{il,t-1}\right) - 1\right] \quad (3.44)$$

Fiscal Authority

The fiscal authority only issues government bonds and has an intertemporal budget constraint involving only government bonds and seiniorage. We model the government bond because we want to model asset prices, and government bond serves as risk-free asset; and we abstract from the fiscal authority's function in the collection of taxation and allocation of public spending because these are beyond the scope of this paper. Therefore, the budget constraint for the fiscal authority is in condition (3.45). The left-hand side expresses what the government has to pay in terms of previous debts and the right-hand side shows the new debts plus seigniorage obtained from printing high-power money.

$$(B_{t-1}^{\alpha} + B_{t-1}^{w} + B_{t-1}^{r})\frac{(1+r_{b,t-1})}{\pi_t} \leq B_t + \frac{M_{t-1}}{\pi_t}\left[R_t^r\left(1 + r_{il,t-1}\right) - 1\right] \quad (3.45)$$

3.6 Equilibrium Conditions

The definition of equilibrium is the condition of the macroeconomic system when every agent maximises its own utility given its budget constraints and law of motions, all market clears and rational expectations hold. The previous section sets up the model for the maximisation problem, and this section summarises market clearing conditions and rational expectations, which close the model.

Market Clearing Conditions

There are eight active markets in the economy, and in each market, prices are fully determined by the supply and demand equilibrium.

The goods market clears when the sum of the demand for private goods and the demand for public goods equals total production.

$$c_t = y_t \qquad < p_{c,t} > \tag{3.46}$$ [9]

The capital market clears when the demand for capital goods equals the supply of capital goods.

$$\tau_t b_{k,t} + (1 - \tau_t) b_{k,t-1} = q_{k,t} \qquad < p_{k,t} > \tag{3.47}$$

The labour market clears when the demand for labour equals the supply of labour.

$$b_{n,t} = q_{n,t} \qquad < p_{n,t} > \tag{3.48}$$

The deposit market clears when the demand for deposits on the liability side of wholesale bank equals the deposits supplied by the household.

$$u_t^w = D_t \qquad < r_{d,t} > \tag{3.49}$$

The interbank market clears when the demand for interbank loans on the liability side on the retail bank equals the supply of interbank loans at the very end of each period.

$$u_t^r = W_t + M_t \qquad < r_{il,t} > \tag{3.50}$$

The corporate loan market clears when total outstanding loans demanded by the firms equal the total outstanding loans supplied by the wholesale bank, and the new loans demanded by the firms demanded at each period equal the new loans supplied by the wholesale bank. The portion of outstanding corporate loans to be paid back as demanded by the firms should equal the portion of outstanding corporate loans – supplied by the retail bank- to be paid back.

$$u_t^\theta = L_t \quad < r_{l,t}, r_{l',t} > \tag{3.51}$$

$$\Delta u_t^\theta = l_t \qquad < r_{l,t}, r_{l',t} > \tag{3.52}$$

$$\delta_t^\theta = \delta_t^r \qquad < r_{l,t}, r_{l',t} > \tag{3.53}$$

The government bond market clears when the sum of the demand for government bonds at the household, the demand for government bonds at the wholesale bank and the demand for government bonds at the retail bank equal the government bonds supplied by the fiscal authority.

$$B_t^\alpha + B_t^w + B_t^r = B_t \qquad < r_{b,t} > \tag{3.54}$$

Rational Expectations

The rational expectations conditions assume the all agents know the structure of the

[9] The equilibrium price of each market is denoted in <>.

model perfectly and have impeccable computational technique, implying that the lending agents are correct in their expectation of the repayment rate for the various loans. Conditions (3.55), (3.56) and (3.57) show that the household, the wholesale bank and the retail bank are correct in their expectations of the repayment rates concerning the loans, i.e. deposits, interbank loans and corporate loans, that will be delivered to them.

$$R_t^w = \begin{cases} v_t^w & u_{t-1}^w > 0 \\ arbitrary, & u_{t-1}^w \leq 0 \end{cases} \tag{3.55}$$

$$R_t^r = \begin{cases} v_t^r & u_{t-1}^r > 0 \\ arbitrary, & u_{t-1}^r \leq 0 \end{cases} \tag{3.56}$$

$$R_t^\theta = \begin{cases} v_t^\theta & u_{t-1}^\theta > 0 \\ arbitrary, & u_{t-1}^\theta \leq 0 \end{cases} \tag{3.57}$$

4. Equilibrium Analysis

In general, our view is consistent with the long-run money neutrality proposition that the RBC and New Keynesian literature suggests. However, unlike the RBC model where neutrality always holds, our model obtains money non-neutrality in the short run equilibrium. Moreover, in start contrast to the New Keynesian approach, where short-run non-neutrality is obtained through Calvo-style nominal rigidity, short-run non-neutrality is driven by the postulated transaction technology in our model, subsequent transactions and investment demand for money. That is to say, liquidity (CIA) and default are the driving force of our result.

Proposition 1. ***Fisher Effect***

Suppose that the household spends money $p_{c,t}c_t > 0$ for buying private goods, deposits $D_t > 0$ into the wholesale bank w, and invests $B_t^{\alpha} > 0$ in government bonds at $\forall t \epsilon T$. Then in any short-run equilibrium, we have

$$\ln\left(1 + r_{b,t}\right) = \ln\left(\frac{U'(c_t;\alpha)}{\beta_\alpha U'(c_{t+1};\alpha)}\right) + \ln(E_t\pi_{t+1})$$

$$\ln\left(1 + r_{d,t}\right) = \ln\left(\frac{U'(c_t;\alpha)}{\beta_\alpha U'(c_{t+1};\alpha)}\right) + \ln(E_t\pi_{t+1}) - \ln(E_t R_{t+1}^{w})$$

Proof. Appendix B

The nominal interest rate of government bonds can be interpreted as risk-free, and is approximately equal to the real interest rate plus inflation. The nominal interest rate of deposits is approximately equal to the real interest rate plus inflation and default risk premium. The 'Fisher Effect' proposition links the nominal interest rate of deposits to consumption streams, and if nominal interest rate of deposit is changed, consumption is affected as well.

Proposition 2. ***Term Structure of Interest Rates***

Suppose that the household invests in government bonds $B_t^{\alpha} > 0$, and market clearing conditions hold in the deposit $D_t > 0$, interest bank loans $W' > 0$, and corporate loans $L_t, l_t > 0$ markets at $\forall t \epsilon T$, then in any short-run equilibrium, we have:

$$1 + r_{b,t} = E_t R_{t+1}^{w}(1 + r_{d,t})$$

$$1 + r_{d,t} < E_t R_{t+1}^{r} \left(1 + r_{il,t}\right)$$

$$1 + r_{il,t} < E_t R_{t+1}^{\theta} \left(1 + r_{l',t}\right)$$

Proof. Appendix B

The 'Term Structure of Interest Rate' proposition explains that all the nominal interest rates are contemporaneously determined. Thus, together with proposition 1, we can conclude that nominal interest rates, real interest rate and inflation are simultaneously derived.

Corollary. ***Money Non-Neutrality***

Supposing that 'Fisher Effect' and 'Term Structure of Interest Rates' propositions hold, 'Fisher Effect' links the nominal interest rate of government bonds and household deposits to consumption streams, the 'Term Structure of Interest Rates' proposition makes a link among the nominal interest rates, and nominal interest rates are approximately equal to real interest rates plus expected inflation and risk premium, which depend on liquidity and default, therefore, CIA and default are the driving force for money non-neutrality.

More specifically, if the central bank injects liquidity into the interbank market, the CIA constraint of the wholesale bank would induce it to lower the nominal interest rate of interbank loans, thus deposit rate, government bond rate and possibly corporate loan rate are accordingly lowered as well, changing consumption streams and production, etc. Thus, the central bank has the ability to control the real economy in the short run. Moreover, as the 'Fisher Effect' and 'Term Structure of Interest Rates' suggest, for defaultable assets, their interest rates bear a risk premium for default, and since CIA link interest rates to consumption streams, default also affects consumption streams via its risk premium on asset prices.

Definition. ***No Arbitrage Conditions***

Agents do not repay more than what they owe, so $R_t^{\theta}, R_t^{w}, R_t^{r} \leq 1$, and they are not rewarded for defaulting on their obligations - $R_t^{\theta}, R_t^{w}, R_t^{r} \geq 0$. Typically, the default penalty on the wholesale bank should be high and the resulting repayment rate should follow suit, because the wholesale bank, which deals with household deposits directly, not only suffers from both reputational damage, but is also susceptible to regulatory damage.

Proposition 3. ***Interest Rate Spreads***

Suppose the wholesale bank w invests in government bonds $B_t^w > 0$ and interbank loans $W_t > 0$, and the retail bank r invests in corporate loans $L_t > 0, l_t > 0$. Market clearing conditions hold in the deposit $D_t > 0$, interest bank loans $W' > 0$, and corporate loans $L_t, l_t > 0$ markets at $\forall t \epsilon T$. Suppose further that banks are mandated by regulatory requirement (NSFR): $0 < c, \delta < 1$, then we obtain in any short-run equilibrium

$$r_{b,t} < r_{d,t} < r_{il,t} < r_{l',t}$$

Typically, the interest rate of corporate loans that have not been paid back this period would be higher than that of corporate loans that are repaid in this period, otherwise firms would be encouraged to extend loan maturity, however, the interest rate of long term corporate loans $r_{l,t}$ depends on the regulation on maturity mismatch, so the relationship between $r_{l',t}$ and $r_{l,t}$ is more of a calibration issue in our model. We conclude

$$r_{b,t} < r_{d,t} < r_{il,t} < r_{l',t}$$

Proof. Appendix B

Together with the 'Fisher Effect' proposition, we can conclude that interest rate spreads are fully determined by risk premiums and regulatory requirements of the banks.

Proposition4. ***On-the-Verge Conditions***

Suppose that 'No Arbitrage Conditions' hold, then in any equilibrium, we obtain:

$$u'(\theta, t) = \frac{\lambda^\theta \delta_t^\theta u_{t-1}^\theta (1 + r_{l',t-1})(1 - v_t^\theta)}{\pi_t}$$
$$u'(w, t) = \frac{\lambda^w u_{t-1}^w (1 + r_{d,t-1})(1 - v_t^w)}{\pi_t}$$
$$u'(r, t) = \frac{\lambda^r u_{t-1}^r (1 + r_{il,t-1})(1 - v_t^r)}{\pi_t}$$

The left-hand-side represents the marginal gain from default and the right-hand-side reflects the marginal loss from default.

1. The borrowing agent will default completely when the marginal gain for zero delivery of the obligations is higher than the marginal loss from default.
2. If at zero delivery the marginal utility gain is less than the marginal disutility from default, then the borrowing agent will default up to the level where the

marginal gain is equal to the marginal loss.

3. The borrowing agent will deliver the obligation fully when the marginal gain for full delivery is lower than the marginal loss.

Proof. Appendix B

In our model, the agent endogenously determines the default. On the one hand, each additional unit of income has a marginal value for the agent; on the other, not delivering an additional unit in accordance with one's contractual obligation and the decision to default incur a marginal penalty. When the marginal utility is higher than the marginal penalty, the agent decides to default on that additional unit of income. Thus, when the time comes to honour the contractual obligation, the borrower can default its promise completely, default partially or deliver the obligation fully.

Proposition 5. ***Interplay between Maturity Mismatch and Default***

A decrease in maturity mismatch inclines the firms and the retail bank to decrease the default rate. From a partial equilibrium perspective, we have

$$\frac{\partial v_t^{\theta}}{\partial \delta_t^{\theta}} > 0 \text{ and } \frac{\partial v_t^{r}}{\partial \delta_t^{r}} > 0$$

Suppose δ_t^{θ} or δ_t^{r} increases, then the average maturity of corporate loans decreases, then the magnitude of default penalty decreases in response, and the repayment rate increases, finally implying a decrease in the default rate. Therefore, from a partial equilibrium perspective, a decrease in maturity mismatch implies a reduction in default of the firms and the retail bank. Therefore, a more stringent NSFR implementation would lead to a decrease in default rate of the firms and the retail bank. Our subsequent impulse response functions confirm that this relationship holds in a dynamic general equilibrium.

There is no direct relationship between maturity mismatch and the wholesale bank's default rate, as the maturity mismatch only exists between the corporate loans and household deposit, and no maturity mismatch exists between the interbank loans and household deposit in our model; therefore, maturity mismatch does not enter the wholesale bank's default penalty directly. We can only rely on impulse response functions to see how maturity mismatch feeds into the wholesale bank's default rate.

Proof. Appendix B

5. Calibration and Bayesian Estimation

There are 28 parameters in the model. Because the set of observable variables that we use does not provide information to estimate all of the parameters, we take the calibrated values of some parameters directly from literature. Table 3 summarises the calibrated parameters from literature.

Table 3: Calibrated parameters

β_α	Discount factor of the household	0.9963
β_θ	Discount factor of the firms	0.9844
β_w	Discount factor of the wholesale bank	0.9927
β_r	Discount factor of the retail bank	0.988
d	Capital stock depreciation rate of the household	0.03
d'	Capital stock depreciation rate of the firms	0.2
e_n	Labour endowment	700
a	Productivity	1
τ	Fraction of capital that gets re-optimised every period	0.2
δ	Fraction of outstanding loans that are paid back	0.7
ρ_a	AR(1) coefficient for productivity shock	0.95
ρ_π	Taylor Rule coefficient for inflation	1.5579
ρ_y	Taylor Rule coefficient for output growth	0.2023
ζ	Backward-looking coefficient in the Taylor Rule	0.9016
ω	Macro-prudential rule (NSFR) coefficient for output growth	0.3

For the rest of parameters, we can use the observables in our model to perform estimation. The observables we use are deposit rate, short-term corporate loan rate, long-term corporate loan rate, the proportion of outstanding loans that are repaid and the repayment rates of the firms and retail bank. We take the observed values of the interest rates and repayment rates mentioned above from Li Lin (2013) and Ahn and Tsomocos (2013), which are derived from the Federal Reserve System Statistics from January 1985 to May 2012. We set the proportion of outstanding loans that are paid back to be 0.65, which is realistic considering out model assumes no stickiness in labour optimisation. We also assume that there is no inflation at steady state. With the actual data of this set of observables, we can estimate the values of implied parameters, summarised in Table 4.

Table 4: Implied parameters

χ_c	Household preference factor for consumption goods	234.1931
χ_k	Household preference factor for capital goods	38.6418
χ_n	Household preference factor for leisure	59.6724
c	Output elasticity to labour	0.4572
λ^{θ}	Default penalty on the firms	1.2606
λ^{w}	Default penalty on the wholesale bank	1.3576
λ^{r}	Default penalty on the retail bank	1.1930
z^{w}	Liquidity penalty on the wholesale bank	0.00415
z^{r}	Liquidity penalty on the retail bank	0.00948
ψ	Maturity mismatch penalty on the retail bank	0.0096
c^{w}	Liquidity ratio of the wholesale bank	0.4049
c^{r}	Liquidity ratio of the retail bank	0.2682
σ^{w}	Risk-aversion parameter of the wholesale bank	0.004
σ^{r}	Risk-aversion parameter of the retail bank	0.634

With the above parameter values, we can obtain all steady states and simulate the time series for each variable. To obtain results that are robust to and consistent with our model, we use the simulated data series and apply Bayesian methods to get the posterior estimates for some model-specific parameters (see An and Schorfheide, 2007).[10] The prior and posterior distributions are displayed in Figure C in Appendix C. Table 5 is a summary of the prior distributions, the posterior mean and 90% credible interval of selected estimated parameters.

[10] The estimation is done using Dynare 4.4.2. The posterior distributions are based on 20,000 draws of the Metropolis-Hastings algorithm.

Table 5: Prior and Posterior Distributions

Parameters	Prior			Posterior	
	Distribution	Mean	SD	Mean	90% C.I
λ^{θ}	Inverse gamma	1.261	0.3	1.2701	[0.8434,1.7049]
λ^{w}	Inverse gamma	1.358	0.3	1.3159	[0.8516,1.7213]
λ^{r}	Inverse gamma	1.193	0.3	1.2493	[0.7645,1.7810]
τ	Normal	0.200	0.05	0.1989	[0.1802,0.2153]
ψ	Inverse gamma	0.010	0.001	0.0099	[0.0082,0.0115]
z^{w}	Inverse gamma	0.004	0.001	0.0041	[0.0027,0.0053]
z^{r}	Inverse gamma	0.009	0.001	0.0094	[0.0077,0.0108]
c^{w}	Normal	0.405	0.05	0.4023	[0.3196,0.4827]
c^{r}	Normal	0.268	0.05	0.2724	[0.1921,0.3588]
χ_{c}	Normal	234.193	50	233.3988	[232.2921,234,5648]
χ_{k}	Normal	38.642	10	37.7017	[22.1184,53.9445]
χ_{n}	Normal	59.672	10	53.5178	[41.6641,65.4998]

With the posteriors, we get the steady states by solving a system of simultaneous equations. In the steady state, the economy is operating in a deterministic competitive equilibrium. The endogenous variables are reported in Table C in Appendix C. Our steady states are in line with 'No Arbitrage Conditions', which imply that agents do not repay more than what they owe and they are not rewarded for default on their obligation as $0 \leq R^{\theta}, R^{w}, R^{r} \leq 1$. Moreover, the interest rates satisfy the 'Interest Rate Spreads' proposition as $r_b \leq r_b \leq r_{il} \leq r_{l'} \leq r_l$.

6. Quantitative Analysis

In this section, we study the real effect of a productivity shock, a monetary policy shock and a macro-prudential policy (NSFR) shock. Firstly, in accordance with standard practice in the literature, we analyse the impact of productivity shock on various real economic variables. Then we present the impulse response functions with respect to policy shocks and analyse the linkages of such shocks to real economic variables.

6.1 Assessing the Responses to Technology Shock

Figure D-1[11] displays the responses of various endogenous variables with respect to a positive technology shock. Firstly, we examine the impulse response functions of key macroeconomic variables. The positive technology shock increases output with the same order of magnitude, shifting outward the supply curve in the goods market and leading to a fall in prices, thus, immediate deflation. A technology boom also leads to a persistent increase in the labour equilibrium path, the shape of which depends on the magnitude of the shock, and reducing unemployment. The major force of the technology boom shifts outward the demand curve for labour, and real wages increase as well. However, the technology boom causes capital investment to fall, which means that the household supplies less capital and its capital stock increases.

Secondly we examine the responses of various asset prices to the positive productivity shock. As can be seen in Figure D-1, the magnitude of deflation is no less than that of the output boom, and the Taylor rule reacts more aggressively to inflation/deflation than output, resulting in more liquidity in the interbank market that is provided by the central bank. The availability of more liquidity in the banking system reduces the interbank loan rate and corporate loan rates. However, the immediate response of the risk-free rate and deposit rate is an increase because the technology boom leads to more demand for saving

[11] All key figures on impulse response functions and welfare analysis are displayed in the Appendix D and E.

or consumption smoothing. Whether there will be a fall in these two rates within six periods depends on the magnitude of the shock. For the large shock, these two rates successively increase and then decrease, and gradually return to steady states.

Thirdly, we analyse the responses of defaults and maturity mismatch. The availability of more liquidity in the banking system reduces the market-determined maturity mismatch because the firms need not postpone repaying their old outstanding loans as much as before, increasing the maturity of the corporate loans. In turn, a decrease in maturity mismatch increases the magnitude of the default punishment, thus, default rates generally fall and then return to steady states, confirming proposition 5 on the interplay between default and maturity mismatch.

Fourthly, we examine the welfare and profitability of various agents. The household's welfare is increased before gradually returning to the steady state, because both consumption and capital stock rise and their effects dominate the disutility from an increase in labour supply. Firms' welfare increases despite decrease in profits after the 4^{th} period because the magnitude of the default penalty is reduced. In general, the retail bank and wholesale bank are worse off at the start because the shorter maturity mismatch reduces profitability of the former and the lower loan-deposit interest rate spread reduces the profitability of the latter.

Finally, we study the major components of the 'Fisher Effect'. The risk-free rate can be decomposed as the real rate and inflation expectation premium, and the risky rates, e.g. the short-term corporate loan rate, can be decomposed as the real rate, inflation expectation premium and default risk premium (Propositions 1 and 2 in Section 4). As seen in the figure, the short-term corporate loan rate and risk-free rate go in opposite directions when hit by a positive technology shock, and the decrease in default drives the decrease of the short-term loan rate, further suppressing the default premium.

6.2 Monetary Policy Experiment

In Figure D-2, we examine the impact of a stringent monetary policy shock. This begins with an analysis of the responses of major macroeconomic variables. When the central bank tightens monetary policy, the decrease in interbank loan supply pushes up the interbank loan rate, whose spill-over effect makes borrowing more costly in general - this results in a persistent increases in all asset prices (Figure D-2). Rising asset prices imply higher financing costs and reduced capital investment for the firm. A low level of capital supply means the household accumulates more capital stock. A low level of borrowing for working capital leads to a decrease in labour demand, thus explaining the fall in labour and real wage. All these factors contribute to a fall in the goods supply. Furthermore, the rise in asset prices generates a liquidity effect and influences household consumption decisions, leading to an immediate decrease in consumption demand, and consequently a decrease in demand for goods. Although both demand and supply decrease in the goods market, the effect of low goods expenditure masks the effect of decreased production and results in an immediate drop in price level, overall contributing to a general deflation.

Next, we analysed the responses of defaults and market-determined level of maturity mismatch. The rise in asset prices, or the rise in borrowing costs, induces the firm to postpone the repayment of old outstanding loans, thus causing an increase in the policy-desire maturity mismatch according to our macro-prudential policy (NSFR) feedback rule. Accordingly, the market-determined level of maturity mismatch increases. However, the increase in maturity mismatch has a heterogeneous impact on the default rates. On the one hand, an increase in maturity mismatch reduces the magnitude of default punishment affecting the firms and the retail bank, so default rates should increase along the equilibrium path; on the other hand, the rise in borrowing costs increases the magnitude of default punishment in general, so default rates should decline. Whether the default rate increases or decreases depends on the dominating factor. In the face of big monetary shocks, the default rates of firms and the retail bank shows a parallel increase with overall maturity mismatch, consistent with Proposition 5.

Finally, we analyse the impact of a monetary contraction on the welfare and profitability of various agents. The household generally benefits. Despite reduced consumption and wages, the household suffers less disutility from labour and derives more utility from more capital stock; moreover, the increase in the deposit rate and government bond rate contributes more proceeds to the household. The firms benefit in the first three periods and then lose out. The firms benefit because the initial increase in maturity mismatch increases their profits directly, but later the effect of costs of borrowing dominates, profits fall and welfare decreases as well.

6.3 Macro-prudential Policy (NSFR) Experiment

Figure D-3 displays the impact of a contraction in the macro-prudential policy NSFR. Firstly, we analyse the responses of major macroeconomic variables and asset prices. The countercyclical feature of the macro-prudential feedback rule and the contractionary nature of this policy shock lead to a decrease in output. Moreover, a contraction in the macro-prudential policy NSFR means the policy-desired level of maturity mismatch becomes lower, reducing the market-determined maturity mismatch. Moreover, a fall in maturity mismatch implies that the firms need to accelerate the repayment of their old outstanding loans, thus leading to a stronger demand for new corporate loans, which increase in the process. As described in the analysis above, defaults generally decrease, so the default premium of corporate loans decreases. According to the Fisher Effect, the risky corporate loan rate increases while its default premium decreases, and safer asset prices should increase to a greater degree to restore equilibrium, which is confirmed in Figure D-3. However, the only asset price that behaves differently is the interbank loan rate. Since the decrease in maturity mismatch means that firms need to repay their old outstanding loans faster, the retail bank does not need to demand as much borrowing as prior to the shock, so the demand for interbank loans decreases, and the interbank rate falls.

Secondly, we analysed the responses of defaults and market-determined maturity mismatch. In the face of a contraction in the macro-prudential policy (NSFR), the policy-desired level of maturity mismatch decreases, reducing the market-determined maturity mismatch. A lower maturity mismatch increases the magnitude of the default penalty for both the firms and the retail bank, leading to the fall in the default rates of both the firms and the retail bank, consistent with Proposition 5. However, a more stringent macro-prudential policy leads to a fall in deposits, reducing the magnitude of the default penalty on the wholesale bank, thus the default rate of the wholesale bank increases.

Thirdly, we analysed the welfares and profitability of various agents in the face of a contraction within the macro-prudential policy (NSFR). Generally, household welfare increases after three quarters， this is mainly due to an increase in household capital stock and a reduction in disutility of labour, despite a slight decrease in consumption. However, the firms and the two banks become worse off because they lose profits due to the contractionary nature of this policy shock.

7. Welfare Analysis

7.1 Welfare Analysis with Comprehensive Shock Processes

We analyse the optimal policy regime of the Taylor rule and the macro-prudential policy (NSFR) rule, and optimise the parameters of these rules in order to maximise the total welfare of the household. More specifically, we use Dynare to perform second-order approximation for the dynamic equations in our model to include second moments as well, so that the steady state value of each variable is the same while the mean of each variable is no longer just its steady state value but also includes the variance of the shock processes, which can now also be affected by policymakers. The mean of each variable consists of the steady state value and the risk-adjusted term. Our objective is to maximise the mean of the household welfare, and we report the welfare gain as:

$$\Delta W_{\alpha} = \frac{(W_{\alpha}^{*} - W_{\alpha}^{ss}) - (W_{\alpha} - W_{\alpha}^{ss})}{W_{\alpha} - W_{\alpha}^{ss}}$$

Where W_{α}^{*} is the risk-adjusted household welfare with optimised rules, W_{α} is the risk-adjusted household welfare with benchmark rules, and W_{α}^{ss} is the steady state value of household welfare.

In Table 6 we analyse three scenarios of optimised policy rules and report the welfare gains in percentage terms compared with the benchmark case. First of all, we optimise the coefficients of both the Taylor rule and the macro-prudential policy (NSFR) rule and obtain the most welfare gains. The optimised coefficients suggest that neither the Taylor rule nor the macro-prudential policy (NSFR) rule should attach too much weight to the backward-looking variables. The Taylor rule should react strongly to inflation while the macro-prudential policy (NSFR) rule should react strongly to output growth, which is a proxy for credit boom in our formulation. Then we optimise the Taylor rule while restricting the macro-prudential rule (NSFR) to the benchmark case and then optimise the macro-prudential rule alone while restricting the Taylor rule to the benchmark case, and we find that most of the welfare gains come from the optimisation of the Taylor rule. This suggests that though the policymakers attach much weight to the backward-looking element of the macro-prudential rule (NSFR), as long as the major component of the monetary policy rule is not backward-looking and can be adjusted flexibly based on current inflation and output growth, the policymakers can still achieve the greater part of the welfare gains for the household. This finding is consistent with how policy is implemented in reality. In reality, macro-prudential rules are usually less flexible than the monetary rule and greater weight is attached to the backward-looking elements.

Table 6: Optimal Monetary and/or Macro-prudential Policy (NSFR)

	ρ_π	ρ_y	ζ	ω	ΔW_α
Optimal TR &NSFR	1.0554	0.5050	0	0.8945	0.0265
Optimal Taylor Rule	1.05	0.4518	0	0.3	0.0221
Optimal NSFR	1.5579	0.2023	0.9016	0.9332	0.0044
Benchmark	1.5579	0.2023	0.9016	0.3	

We also display impulse response functions of key variables in Appendix E. In general, with the optimised Taylor rule and macro-prudential policy (NSFR) rule, variables are much less volatile when reacting to shocks. Note that Table 6 is an aggregate optimisation exercise involving all shock processes hitting the system simultaneously. When there is only one shock process, then the welfare picture might be different, so we use impulse response functions across policy regimes to analyse shocks one at a time. Hereafter, we denote the estimated policy rules as Regime 0, the optimal macro-prudential rule (NSFR) and the estimated monetary rule as Regime 1, the optimal monetary rule and the estimated macro-prudential rule (NSFR) as Regime 2, and the optimal monetary rule and the optimal macro-prudential rule (NSFR) as Regime 3.

7.2 Welfare Analysis with a Positive Technology Shock

To begin with, we analysed the impulse response functions with respect to a positive technology shock across policy regimes. In Figure E-1, in the face of a positive technology shock, there are few changes in output, capital investment, inflation, wage, firms' capital stock, household capital stock, capital price, government bonds held by the household, total government bonds, wholesale bank default and household welfare across different policy regimes, while other variables exhibit changes with varying degrees of magnitude. We compare the welfare changes of various agents across different regimes and probe the reasons for such changes.

For the household, the improvement in welfare as we optimise various policy rules is not significant, as shown in Table 6, and even with all shock processes, the welfare gains are marginal. However, as we shall see, even though our optimising objective is the household welfare and we achieve tiny welfare gains compared with the estimated case, our optimised rules would induce big welfare improvement for some other agents in the economy.

For the firms, the optimal policy regimes are Regime 2 and Regime 3. The transmission mechanism works as follows: when a positive technology shock hits the economy, Regime 2 and Regime 3 reacts more strongly to output growth than Regime 0 and Regime 1. This potent counter-cyclical feature dampens demand for corporate loans and interbank loans compared with Regime 0 and Regime 1. Therefore, even though in the time dimension, the equilibrium paths of interbank loans and corporate loans all increase and then return to steady states, cross-sectionally, the increases in Regime 2 and Regime 3 are not as strong as those observed in Regime 0 and Regime 1. This means that the magnitude of default in Regime 2 and Regime 3 is larger than that in Regime 0 and Regime 1. Accordingly, firms' default rates and maturity mismatch in Regime 2 and 3 are larger than those in Regime 0 and Regime 1. Larger default rates and maturity mismatch in Regime 2 and 3 increase firms' profitability, and because the effects on regulation penalties are not significant, firms' welfares in Regime 2 and Regime 3 are larger than those in Regime 0 and Regime 1.

For the retail bank, Regime 1 and Regime 3 are optimal from the second period onward. The common feature of Regime 1 and Regime 3 is that they both contain the optimal macro-prudential (NSFR) rule that reacts to output growth with a stronger force than Regime 0 and Regime 2, so in Regime 1 and Regime 3, the maturity mismatch level is smaller, which reduces the retail bank default rate, consistent with our proposition and analysis in the previous sections. As in E-1, the default of retail bank is smaller in Regime 1 and Regime 3 than in Regime 0 and Regime 2, and it is likely to reduce the default penalty imposed on the retail bank. Moreover, as the macro-prudential rule (NSFR) is more aggressive in reducing maturity mismatch in Regime 1 and Regime 3, this counter-cyclical feature induces a stronger demand for consumption smoothing and pushes up the asset price of government bonds. This effect increases the profitability of the retail bank. Overall, the retail bank is moderately better off in Regime 1 and Regime 3 than in Regime 0 and Regime 2.

For the wholesale bank, Regime 2 and Regime 3 are optimal with very large welfare gains when compared with the other regimes, and they result in approximately the same welfare responses. As analysed in the previous section, a technology shock negatively affects welfare for the wholesale bank. Compared with Regime 0 and Regime 1, the decrease of welfare in Regime 2 or Regime 3 is smaller. The reasons are as follows: when a positive technology shock hits the economy, Regime 2 and Regime 3 reacts to output growth counter-cyclically with a stronger force, which shrinks the demand for loans in general, leading to a smaller demand for deposits. Thus, the deposit rate is generally higher in Regime 2 and Regime 3 than in Regime 0 and Regime 1 in general. The same argument goes for the interbank loan rate. Moreover, the risk-free rate is much higher in Regime 2 and Regime 3, because Regime 2 and Regime 3 react strongly to output growth counter-cyclically, inducing a stronger demand for consumption smoothing and pushing up the risk-free rate. Thus, the differential between asset return and deposit cost is the biggest in Regime 2 and Regime 3. In terms of portfolio allocation, the wholesale bank invests more in government bonds and less in interbank bank loans in Regime 2 and Regime 3. The differences in portfolio allocation and asset prices across regimes are the reason why the wholesale bank profits more, and thus has a higher welfare, in Regime 2 and Regime 3.

7.3 Welfare Analysis with a Contractionary Monetary Shock

As in Figure E-2, generally speaking, when facing a contractionary monetary shock alone, the Regime 2 and Regime 3 greatly reduce the volatility of almost all endogenised variables. Due to the shock nature, both of these regimes have their Taylor rule react strongly to output growth. The household welfare, apart from the first 4 periods in which the welfare improves, generally deteriorates quite moderately in Regime 2 and Regime 3. To understand why, we decompose household welfare into consumption, labour and household capital stock. As in Figure E-2, consumption (output) improves in Regime 2 and Regime 3, increasing overall welfare. However, disutility from labour is larger and utility from household capital stock is smaller in Regime 2 and Regime 3, so overall welfare is slightly lower.

As for the firms, welfare is greater in Regime 2 and Regime 3 after the third period, and this welfare gain mainly comes from a smaller default in the first 4 periods and a larger profit after the third period. More specifically, in Regime 2 and Regime 3, the Taylor rule has no backward-looking element. A contractionary shock in monetary policy results in little persistence in the decrease in asset prices, as in Figure E-2, and asset prices go back to steady states in the second period. This means firms' financing cost is lower in Regime 2 and Regime 3, and in turn profitability generally is generally higher. Moreover, this contractionary monetary shock in Regime 2 and Regime 3 lowers the firms' financing need more than in Regime 0 and Regime 1, so the disutility of the default penalty is possibly lower. Overall, the firms' welfare is greater in Regime 2 and Regime 3 after the third period.

The retail bank is better off in Regime 0 and Regime 1, and the main driving force for such welfare gain is better profitability. As analysed before, the Taylor rule has no backward-looking element in Regime 2 and Regime 3, so the asset prices are lower compared with Regime 0 and Regime 1. Although the interbank loan rate is also persistently higher in Regime 0 and Regime 1, the increase in the corporate loan rate and risk-free rate dominates, bringing in higher profit for the firms in these two regimes. Note that the magnitude of welfare gains is smaller than that of profitability gains in Regime 0 and Regime 1, and this would mean the disutility from default penalty in Regime 0 and Regime1 is larger than that in Regime 2 and Regime 3.

In general, the wholesale bank is better off in Regime 2 and Regime 3 than in Regime 0 and Regime 1, and the main driving force for this welfare gain is a better profitability in Regime 2 and Regime 3. The reasoning follows a similar vein as the retail bank case. As analysed before, the Taylor rule has no backward-looking element in Regime 2 and Regime 3, so the asset prices are lower compared with those in Regime 0 and Regime 1. Although the interbank loan rate and risk-free rate are also persistently higher in Regime 0 and Regime 1, the increase in the deposit rate dominates, resulting in a smaller loan-deposit spread and bringing in less profit for the wholesale bank in these two regimes, so the wholesale bank enjoys higher profit in Regime 2 and Regime 3. Note that the magnitude of welfare gains is smaller than that of profitability gains in Regime 2 and Regime 3, and this would mean the disutility from default penalty in Regime 2 and Regime 3 is larger than that in Regime 0 and Regime 1.

7.4 Welfare Analysis with a Contractionary Macro-prudential Policy (NSFR) Shock

As in Figure E-3, generally speaking, when facing a contractionary macro-prudential (NSFR) shock, Regime 1 and Regime 3 greatly reduce the volatility of endogenised variables and should be the desirable regimes. Due to the nature of the shock, both of these regimes have the macro-prudential (NSFR) rule react strongly to output growth.

Specifically for the household, after the third period, Regime 1 and Regime 3 are actually slightest less desirable than Regime 0 and Regime 2. To understand why, we decompose household welfare into utility from consumption and holding capital stock, and disutility from supplying labour. The household enjoys more consumption but less capital stock in Regime 1 and Regime 3, and moreover, the disutility from labour is larger in Regime 1 and 3 than in Regime 0 and Regime 2. The overall effect is that the household is slightly better off in Regime 0 and Regime 2.

The firms are much better off in Regime 1 and Regime 3, and the main reason for the welfare gain is higher profitability. As we see in Figure E-3, a contractionary macro-prudential (NSFR) policy shock drives up all asset prices except the interbank loan rate. In Regime 1 and Regime 3, the increase in the corporate loan rate is not as big as that in Regime 0 and Regime 2, so the financing cost for the firms is lower, and the firms enjoy higher profitability in Regime 1 and Regime 3. Since the magnitude of the profit increase is larger than that of the welfare improvement in Regime 1 and Regime 3, the disutility from the default penalty should be larger in these two regimes.

The retail bank is also better off in Regime 1 and Regime 3. And the main driver for the welfare gain is higher profitability in these two regimes. Facing a contractionary macro-prudential policy (NSFR) shock, the reduction in maturity mismatch is smaller in Regime 1 and Regime 3 since the policy rule reacts more strongly to business cycle fluctuations. This would mean the retail bank holds much longer corporate loans, and long-term corporate loans have a higher asset price than short-term corporate loans; plus firms' default rate is very small in these two regimes. Therefore, the retail bank enjoys a higher profit, thus a higher welfare in these two regimes.

The wholesale bank is better off in Regime 1 and Regime 3 as well because it enjoys a much higher profitability in these two regimes. The main driving force for the profitability gain is the increase in the loan-deposit spread. In Regime 1 and Regime 3 where the macro-prudential policy (NSFR) reacts more strongly to business fluctuations, the fall in the interbank loan rate is smaller than in Regime 0 and Regime 2, while the increase in the deposit rate is higher. Thus, the interbank loan-deposit spread is higher in Regime 1 and

Regime 3 is higher than in Regime 0 and 2. However, judging by the impulse response functions that the magnitude of welfare gain in these two regimes compared with Regime 0 and Regime 2 is smaller than that of the profitability gain, and the disutility from default penalty and liquidity penalty should be higher in Regime 1 and Regime 3.

7.5 Robustness Results if Shock Identification is Feasible

In 7.1, we achieve optimised rules given all shock processes simultaneously hitting the system. As seen in impulse response functions under various regimes, endogenous variables respond differently conditional on shocks. We conduct an additional robustness result by optimising the Taylor rule and the macro-prudential (NSFR) policy rule conditional on shock types as if the central bank could identify the source of the shock. To this end, we simulate the model with the technology shock only, the labour shock only, the capital shock only, the monetary shock only, or the macro-prudential policy shock only. And the optimal policy rules are quite different given different shocks, as in Table 7. The optimised rules are similar conditional on technology shock and labour endowment shock, and they differ from the optimised monetary rule and optimised macro-prudential rule in Table 6 in that they react more strongly to output growth and attach much more weight to backward-looking elements. Conditional on capital endowment shock, the optimal monetary rule has a backward-looking element, reacting very aggressively to inflation but very mildly to output growth, and the optimal macro-prudential rule reacts somewhat counter-cyclically to output growth. Conditional on monetary shock, the optimal monetary policy has little backward-looking element, but reacts very aggressively to inflation and somewhat strongly to output growth, and the optimal macro-prudential policy reacts very aggressively to business cycle fluctuations. Given macro-prudential policy shock, the optimal monetary rule has the backward-looking element and reacts strongly to inflation, mildly to output growth. And the optimal macro-prudential policy reacts very aggressively to business cycle fluctuations.

Table 7: Optimal monetary and macro-prudential policy (NSFR) conditional on shocks

Technology Shock	ρ_π	ρ_y	ζ	ω
Optimal TR &NSFR	1.05	0.9996	0.949	0.9838
Labour Endowment Shock	ρ_π	ρ_y	ζ	ω
Optimal TR &NSFR	1.05	1	0.9481	0.9881
Capital Endowment Shock	ρ_π	ρ_y	ζ	ω
Optimal TR &NSFR	5	0.001	0.691	0.0492
Monetary Policy Shock	ρ_π	ρ_y	ζ	ω
Optimal TR &NSFR	2.0274	0.6256	0.0004	0.9987
Macro-prudential Shock	ρ_π	ρ_y	ζ	ω
Optimal TR &NSFR	1.2413	0.1808	0.7506	0.9718

8. Conclusions and Future Research Directions

In this paper, we have built a DSGE framework to incorporate two frictions of the heterogeneous banking sector: endogenous default and maturity mismatch. Through modelling money via CIA constraints and non-pecuniary regulatory penalties, we have made relevant the monetary policy and the macro-prudential policy on maturity mismatch, namely, NSFR. We have shown that CIA is a good alternative to Calvo-style rigidity in New Keynesian literature in modelling money neutrality, and that endogenous default results in a risk premium in various asset prices. Most importantly, we have shown the relationship between maturity mismatch and endogenous default and their interactions alongside business cycle fluctuations. We have found that a reduction in maturity mismatch between the corporate loans and household deposits typically reduces the default rates of the firms and the retail bank.

To see how default, maturity mismatch and relevant policy rules feed into the macroeconomic system, we simulate impulse response functions of endogenous variables conditional on various shock processes. Moreover, to analyse how macro-prudential policy NSFR influence the macroeconomic system, we postulate a macro-prudential policy rule in a similar fashion as the monetary policy rule. In traditional New Keynesian literature where the financial system is assumed as a perfect credit channel, policy analysis is primarily on the monetary policy rule. But when we add financial frictions to the DSGE framework, we need to incorporate the macro-prudential policy rule that deals with financial frictions. To see the interplay between the monetary policy and macro-prudential policy, we conduct welfare analysis by optimising the coefficients of the monetary policy rule and macro-prudential policy rule. We have found that given all shock processes, both rules should bear counter-cyclical features; in particular, the monetary policy rule should react aggressively to inflation, and moderately to output growth, and attach little rule-of-thumb backward-looking element, while the macro-prudential policy rule should react aggressively to output growth and bear little rule-of-thumb backward-looking element. We understand that in reality, for political reasons, etc., the central bank tends not to adjust macro-prudential rules very frequently, and that is to say macro-prudential rules may bear significant rule-of-thumb backward-looking element. So we restrict the macro-prudential rule to react with much heavier weight on the backward-looking variable and have found that the welfare loss compared with the first best is insignificant.

However, our framework is not without its limitations. To carry out future research, we have identified at least three directions. Firstly, our model builds upon the assumption of firms' infrequent adjustment of capital in order to model firms' need for longer corporate loans and capture maturity mismatch. One future research direction is to probe the nature of this assumption and analyse the reason underlying the infrequent adjustment of capital. Moreover, we can add a capital-producing firm, which better captures how the firm drives the economy to move forward. We believe these two extensions can help us draw richer implications of maturity mismatch for business cycles. Secondly, since our model only focuses on one macro-prudential policy tool (NSFR), we can naturally extend our model – along the lines of the Goodhart, Kashyap, Tsomocos and Vardoulakis (2012) - to assess a comprehensive set of macro-prudential policies, such as Loan-to-Value Ratio, Capital Requirement, and Liquidity Coverage Ratio, and perform quantitative analysis on their interactions with the monetary policy and the joined impacts on the macroeconomic system with an imperfect financial market. Thirdly, our DSGE framework is useful in analysing the short-term transmission mechanism of macro-prudential policies and endogenous default. But to understand how default is endogenised in the context of information asymmetry and to analyse how macro-prudential policies can reduce moral hazards in the financial market and prevent systemic crisis in the long run, we need to apply the principle-agent framework.

In a nutshell, we have proposed a DSGE framework to incorporate maturity mismatch and its macro-prudential instrument and conducted welfare analysis from a pre-crisis risk management perspective. Since our paper analyses frictions in the financial market and focuses on a specific macro-prudential policy tool that deals with financial frictions, it formally analyses the interactions between the macro-prudential policy and monetary policy, and complements the New Keynesian literature, which builds upon the assumption of a frictionless financial market and focuses mainly on the use of monetary policy rule to manage the economy.

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Appendix

A. First order conditions

FOCs of the Household

Setting up Lagrangian with η_t^α being the lagrangian multiplier at period t.

$$\frac{\partial L(\alpha,t)}{\partial c_t}: \frac{\mathcal{X}_c}{c_t} - \eta_t^\alpha = 0 \qquad \text{A(1)}$$

$$\frac{\partial L(\alpha,t)}{\partial q_t^k}: \frac{\mathcal{X}_k}{k_t^\alpha} = E_t \beta_\alpha p_{k,t} \frac{\eta_{t+1}^\alpha}{\pi_{t+1}} - E_t \beta_\alpha^2 (1-d) p_{k,t+1} E_t \frac{\eta_{t+2}^\alpha}{\pi_{t+2}} \qquad \text{A(2)}$$

$$\frac{\partial L(\alpha,t)}{\partial q_{n,t}}: \frac{\mathcal{X}_n}{(e_{n,t} - q_{n,t})\ p_{n,t}} = \beta_\alpha E_t \frac{\eta_{t+1}^\alpha}{\pi_{t+1}} \qquad \text{A(3)}$$

$$\frac{\partial L(\alpha,t)}{\partial D_t}: \frac{\eta_t^\alpha}{(1+r_{d,t})} = E_t \beta_\alpha \frac{\eta_{t+1}^\alpha R_{t+1}^w}{\pi_{t+1}} \qquad \text{A(4)}$$

$$\frac{\partial L(\alpha,t)}{\partial B_t^\alpha}: \frac{\eta_t^\alpha}{(1+r_{b,t})} = E_t \beta_\alpha \frac{\eta_{t+1}^\alpha}{\pi_{t+1}} \qquad \text{A(5)}$$

FOCs of the firm

Setting up Lagrangian with η_t^θ being the lagrangian multiplier at period t.

$$\frac{\partial L(\theta,t)}{\partial b_{n,t}}: E_t \beta_\theta \left(\frac{a_t \left(k_{t-1}^\theta\right)^c (1-c) \left(b_{n,t}\right)^{-c}}{\pi_{t+1}} \right) = \eta_t^\theta p_{n,t} \qquad \text{A(6)}$$

$$\frac{\partial L(\theta,t)}{\partial b_{k,t}}: E_t \beta_\theta^2 \left(\frac{a_{t+1} c (k_t^\theta)^{c-1} b_{n,t+1}^{1-c}}{\pi_{t+2}} \right) \tau + E_t \beta_\theta^3 \left(\frac{a_{t+2} c \left(k_{t+1}^\theta\right)^{c-1} b_{n,t+2}^{1-c}}{\pi_{t+3}} \right) (1-\tau) = \eta_t^\theta \tau p_{k,t} + E_t \beta^\theta \left(\eta_{t+1} + \eta_{t+1}^\theta\right) p_{k,t+1} (1-\tau) - E_t \beta_\theta (1-d) \eta_{t+1}^\theta \tau p_{k,t+1} - E_t \beta_\theta^2 (1-d) \left(\eta_{t+2} + \eta_{t+2}^\theta\right) p_{k,t+2} (1-\tau) \qquad \text{A(7)}$$

$$\frac{\partial L(\theta,t)}{\partial u_t^\theta}: \eta_t^\theta + E_t \beta^\theta \eta_{t+1} \left(1 - \delta_{t+1}^\theta\right) = E_t \beta_\theta \left[\frac{\left(1-\delta_{t+1}^\theta\right)(r_{l,t}+1)}{\pi_{t+1}} + \frac{\delta_{t+1}^\theta \left(1 + r_{l',t}\right)}{\pi_{t+1}} \right] \qquad \text{A(8)}$$

$$\frac{\partial L(\theta,t)}{\partial \delta_t^\theta}: \frac{\left(r_{l,t-1} - r_{l',t-1}\right)}{\pi_t} = \eta_t \qquad \text{A(9)}$$

$$\frac{\partial L(\theta,t)}{\partial v_t^\theta}: \frac{\lambda_\theta \delta_t^\theta u_{t-1}^\theta (1 + r_{l',t-1})(1 - v_t^\theta)}{\pi_t} = 1 \qquad \text{A(10)}$$

FOCs of the wholesale bank

$$\frac{\partial L(w,t)}{\partial B_t^w}:\frac{\eta_t^w-z^w(1-c^w)}{1+r_{b,t}}=\beta_w E_t\frac{1}{\pi_{t+1}(\Omega_{t+1}^w)^{\sigma^w}} \qquad A(11)$$

$$\frac{\partial L(w,t)}{\partial W_t'}:\frac{\eta_t^w+z^w c^w}{1+r_{il,t}}=\beta_w E_t\frac{R_{t+1}^r}{\pi_{t+1}(\Omega_{t+1}^w)^{\sigma^w}} \qquad A(12)$$

$$\frac{\partial L(w,t)}{\partial v_t^w}:\frac{1}{(\Omega_t^w)^{\sigma^w}}=\frac{\lambda_w u_{t-1}^w(1+r_{d,t-1})(1-v_t^w)}{\pi_t} \qquad A(13)$$

$$\frac{\partial L(w,t)}{\partial u_t^w}:\frac{\eta_t^w}{(1+r_{d,t})}=E_t\beta_w\frac{1}{\pi_{t+1}(\Omega_{t+1}^w)^{\sigma^w}} \qquad A(14)$$

FOCs of the retail bank

$$\frac{\partial L(r,t)}{\partial B_t^r}:\frac{\eta_t^r-z^r(1-c^r)}{1+r_{b,t}}=\frac{\beta_r}{\pi_{t+1}(\Omega_{t+1}^r)^{\sigma^r}} \qquad A(15)$$

$$\frac{\partial L(r,t)}{\partial L_t}:-\eta_t^r+E_t\beta_r\left[\frac{(1-\delta_{t+1}^r)(r_{l,t}+1)+R_{t+1}^\theta\delta_{t+1}^r(1+r_{l',t})}{\pi_{t+1}(\Omega_{t+1}^r)^{\sigma^r}}-\psi(\delta_{t+1}-\delta_{t+1}^r)\right]-z^r c^r=0 \qquad A(16)$$

$$\frac{\partial L(r,t)}{\partial v_t^r}:-\frac{1}{(\Omega_t^r)^{\sigma^r}}+\frac{\lambda_r u_{t-1}^r(1+r_{il,t-1})(1-v_t^r)}{\pi_t}=0 \qquad A(17)$$

$$\frac{\partial L(r,t)}{\partial \delta_t^r}:\left[-r_{l,t-1}-1+R_t^\theta(1+r_{l',t-1})\right]\frac{1}{\pi_t(\Omega_t^r)^{\sigma^r}}+\psi=0 \qquad A(18)$$

$$\frac{\partial L(r,t)}{\partial u_t^r}:\frac{\eta_t^r}{1+r_{il,t}}=E_t\beta_r\frac{1}{\pi_{t+1}(\Omega_{t+1}^r)^{\sigma^r}} \qquad A(19)$$

Since this paper introduces maturity mismatch between corporate loans and deposits through modelling loan dynamics $L_t=(1-\delta_t^r)L_{t-1}+l_t$. A trick is used when deriving first order conditions. To demonstrate, we show how we get first-order-conditions A(8) and A(9).

Firstly we consider the separate constraints (3.11) and (3.14). We maximise (3.8) subject to (3.11) and (3.14).

$$\frac{\partial L(\theta,t)}{\partial \Delta u_t^\theta}:\left[\frac{\beta_\theta(1-\delta_{t+1}^\theta)r_{l,t}}{\pi_{t+1}}+\frac{\beta_\theta v_{t+1}^\theta\delta_{t+1}^\theta(1+r_{l',t})}{\pi_{t+1}}-\frac{\beta_\theta(1-v_{t+1})^2(\delta_{t+1}^\theta)^2u_t^\theta(1+r_{l',t})^2}{\pi_{t+1}^2}\right]+$$

$$\left[\frac{\beta_\theta^2(1-\delta_{t+2}^\theta)(1-\delta_{t+1}^\theta)r_{l,t+1}}{\pi_{t+2}}+\frac{\beta_\theta^2 v_{t+2}^\theta\delta_{t+2}^\theta(1+r_{l',t+1})(1-\delta_{t+1}^\theta)}{\pi_{t+2}}-\frac{\beta_\theta^2(1-v_{t+2})^2(\delta_{t+2}^\theta)^2u_{t+1}^\theta(1+r_{l',t+1})^2}{\pi_{t+2}^2}\right]+$$

$$\cdots=\eta_t^\theta \qquad A(20)$$

Substitute A(8) into A(19), then we get

$$\left[\frac{\beta_\theta(1-\delta_{t+1}^\theta)r_{l,t}}{\pi_{t+1}}+\frac{\beta_\theta\delta_{t+1}^\theta\left(1+r_{l',t}\right)}{\pi_{t+1}}\right]+\left[\frac{\beta_\theta^2(1-\delta_{t+2}^\theta)(1-\delta_{t+1}^\theta)r_{l,t+1}}{\pi_{t+2}}+\frac{\beta_\theta^2\delta_{t+2}^\theta\left(1+r_{l',t+1}\right)(1-\delta_{t+1}^\theta)}{\pi_{t+2}}\right]+\cdots=\eta_t^\theta \qquad \text{A(21)}$$

Move A(21) forward by one period, we get

$$\left[\frac{\beta_\theta(1-\delta_{t+2}^\theta)r_{l,t+1}}{\pi_{t+2}}+\frac{\beta_\theta\delta_{t+2}^\theta\left(1+r_{l',t+1}\right)}{\pi_{t+2}}\right]+\left[\frac{\beta_\theta^2(1-\delta_{t+3}^\theta)(1-\delta_{t+2}^\theta)r_{l,t+2}}{\pi_{t+3}}+\frac{\beta_\theta^2\delta_{t+3}^\theta\left(1+r_{l',t+2}\right)(1-\delta_{t+2}^\theta)}{\pi_{t+3}}\right]+\cdots=\eta_{t+1}^\theta \qquad \text{A(22)}$$

Multiply A(22) with $\beta_\theta\left(1-\delta_{t+1}^\theta\right)$ and use A(21) to subtract it, then from the second term of A(20) to infinity, all the terms are cancelled out, and then we get A(9)

$$E_t\beta_\theta\left[\frac{\left(1-\delta_{t+1}^\theta\right)r_{l,t}}{\pi_{t+1}}+\frac{\delta_{t+1}^\theta\left(1+r_{l',t}\right)}{\pi_{t+1}}\right]=\eta_t^\theta-E_t\eta_{t+1}^\theta\beta_\theta(1-\delta_{t+1}^\theta)$$

Then we maximise the objective function with respect to δ_t^θ.

$$\left[\frac{u_{t-1}^\theta r_{l,t-1}}{\pi_t}-\frac{u_{t-1}^\theta\left(1+r_{l',t-1}\right)}{\pi_t}\right]+\left[\frac{\beta_\theta(1-\delta_{t+1})u_{t-1}^\theta r_{l,t}}{\pi_{t+1}}+\frac{\beta_\theta u_{t-1}^\theta\delta_{t+1}^\theta\left(1+r_{l',t}\right)}{\pi_{t+1}}\right]+$$

$$\left[\frac{\beta_\theta^2(1-\delta_{t+2}^\theta)(1-\delta_{t+1}^\theta)u_{t-1}^\theta r_{l,t+1}}{\pi_{t+2}}+\frac{\beta_\theta^2\delta_{t+2}^\theta\left(1+r_{l',t+1}\right)(1-\delta_{t+1}^\theta)u_{t-1}^\theta}{\pi_{t+2}}\right]+\cdots=0 \qquad \text{A(23)}$$

Multiply A(21) with u_{t-1}^θ and then substitute into A(23), we get A(10)

$$\frac{\left(1+r_{l',t-1}-r_{l,t-1}\right)}{\pi_t}=\eta_t^\theta$$

Secondly, we can use the combined constraint $\left(1-\delta_t^\theta\right)u_{t-1}^\theta+p_{n,t}b_{n,t}+p_{k,t}b_{k,t}\le u_t^\theta$, and maximise the objective function with respect to δ_t^θ and u_t^θ, and the implementation is quite straightforward. FOCs are the same as A(9) and A(10).

In a similar fashion, we can get A(16) and A(18) by using either the separate constraints or the combined constraint. Using the separate constraint, we first maximise the retail bank's objective function with respect to l_t^r.

$$\frac{\partial L(r,t)}{\partial l_t^r}:[\beta_r\left(\frac{(1-\delta_{t+1}^r)r_{l,t}+R_{t+1}^\theta\delta_{t+1}^r(1+r_{l't})}{\pi_{t+1}\Omega_{t+1}^r}-\psi(\delta-\delta_{t+1}^r)\right)-z^rc^r]+$$

$$\left[\beta_r^2\left(\frac{(1-\delta_{t+2}^r)(1-\delta_{t+1}^r)r_{l,t+1}+R_{t+2}^\theta\delta_{t+2}^r(1-\delta_{t+1}^r)\left(1+r_{l',t+1}\right)}{\pi_{t+2}\Omega_{t+2}^r}-\psi(\delta-\delta_{t+2}^r)(1-\delta_{t+1})\right)-\beta_rz^rc^r(1-\delta_{t+1})\right]+\cdots=\eta_t^r+\beta_r(1-\delta_{t+1}^r)\eta_{t+1}^r+\beta_t^2(1-\delta_{t+2}^r)(1-\delta_{t+1}^r)\eta_{t+2}^r+\cdots \qquad \text{A(24)}$$

Moving A(24) one period forward,

$$[\beta_r\left(\frac{(1-\delta^r_{t+2})r_{l,t+1}+R^{\theta}_{t+2}\delta^r_{t+2}(1+r_{l't+1})}{\pi_{t+2}\Omega^r_{t+2}}-\psi(\delta-\delta^r_{t+2})\right)-z^rc^r]\ +$$

$$\left[\beta_r^2\left(\frac{(1-\delta^r_{t+3})(1-\delta^r_{t+2})r_{l,t+2}+R^{\theta}_{t+3}\delta^r_{t+3}(1-\delta^r_{t+2})\left(1+r_{l',t+2}\right)}{\pi_{t+3}\Omega^r_{t+3}}-\psi(\delta-\delta^r_{t+3})(1-\delta_{t+2})\right)-\beta_r z^rc^r(1-\right.$$

$$\left.\delta_{t+2})\right]+\cdots=\eta^r_{t+1}+\beta_r(1-\delta^r_{t+2})\eta^r_{t+2}+\beta_t^2(1-\delta^r_{t+3})(1-\delta^r_{t+2})\eta^r_{t+3}+\cdots\quad \text{A(25)}$$

Multiply (25) by $\beta_r(1-\delta^r_{t+1})$ and subtract A(24), we get

$\beta_r\left(\frac{(1-\delta^r_{t+1})r_{l,t}+R^{\theta}_{t+1}\delta^r_{t+1}(1+r_{l't})}{\pi_{t+1}\Omega^r_{t+1}}-\psi(\delta-\delta^r_{t+1})\right)-z^rc^r=\eta^r_t$, which is the same as A(16).

Then we maximise the retail bank's objective function with respect to δ^r_t.

$$\frac{\partial L(r,t)}{\partial\delta^r_t}:\left[\frac{1}{\pi_t\Omega_t}\left(-r_{l,t-1}+R^{\theta}_t\left(1+r_{l',t-1}\right)\right)+\psi+z^rc^r\right]+\beta_r[\frac{1}{\pi_{t+1}\Omega_{t+1}}\left(-(1-\delta^r_{t+1})r_{lt}-\right.$$

$$\left.R^{\theta}_{t+1}\delta^r_{t+1}\left(1+r_{l',t}\right)\right)+\psi(\delta-\delta^r_{t+1})+z^rc^r(1-\delta^r_{t+1})]+\beta_r^2[\frac{1}{\pi_{t+2}\Omega_{t+2}}\left(-(1-\delta^r_{t+2})(1-\right.$$

$$\left.\delta^r_{t+1})r_{l,t+1}-R^{\theta}_{t+2}\delta^r_{t+2}(1-\delta^r_{t+1})\left(1+r_{l',t+1}\right)\right)+\psi(\delta-\delta^r_{t+2})(1-\delta^r_{t+1})+z^rc^r(1-$$

$$\delta^r_{t+2})(1-\delta^r_{t+1})]\ldots=-\eta^r_t-\beta_r(1-\delta^r_{t+1})\eta^r_{t+1}-\beta_r^2(1-\delta^r_{t+2})(1-\delta^r_{t+1})\eta^r_{t+2}\ldots$$

A(26)

Move A(26) one period forward,

$$\left[\frac{1}{\pi_{t+1}\Omega_{t+1}}\left(-r_{l,t}+R^{\theta}_{t+1}\left(1+r_{l',t}\right)\right)+\psi+z^rc^r\right]+\beta_r[\frac{1}{\pi_{t+2}\Omega_{t+2}}\left(-(1-\delta^r_{t+2})r_{lt+1}-\right.$$

$$\left.R^{\theta}_{t+2}\delta^r_{t+2}\left(1+r_{l',t+1}\right)\right)+\psi(\delta-\delta^r_{t+2})+z^rc^r(1-\delta^r_{t+2})]+\beta_r^2[\frac{1}{\pi_{t+3}\Omega_{t+3}}\left(-(1-\delta^r_{t+3})(1-\right.$$

$$\left.\delta^r_{t+2})r_{l,t+2}-R^{\theta}_{t+3}\delta^r_{t+3}(1-\delta^r_{t+2})\left(1+r_{l',t+2}\right)\right)+\psi(\delta-\delta^r_{t+2})(1-\delta^r_{t+2})+z^rc^r(1-$$

$$\delta^r_{t+3})(1-\delta^r_{t+2})]\ldots=-\eta^r_{t+1}-\beta_r(1-\delta^r_{t+2})\eta^r_{t+2}-\beta_r^2(1-\delta^r_{t+3})(1-\delta^r_{t+2})\eta^r_{t+3}\ldots\quad \text{A(27)}$$

Multiplying A(27) with $\beta_r(1-\delta^r_{t+1})$ and subtract A(26), we get

$$\left[-r_{l,t-1}+R^{\theta}_t\left(1+r_{l',t-1}\right)\right]\frac{1}{\pi_t\Omega^r_t}+\psi=\beta_r(1-\delta^r_{t+1})\{\left[-r_{l,t-1}+R^{\theta}_t\left(1+r_{l',t-1}\right)\right]\frac{1}{\pi_t\Omega^r_t}+\psi\}\quad \text{A(28)}$$

Let $A_t+\psi$=$\left[-r_{l,t-1}+R^{\theta}_t\left(1+r_{l',t-1}\right)\right]$, and $k=\frac{1}{\beta_r(1-\delta^r_{t+1})}$, $k>1$

A(28) becomes $A_{t+1}+\psi=k(A_t+\psi)$, if $A_t+\psi\neq 0$, then A_{t+1} is explosive, so $A_t+\psi=0$ is the only solution. In other words, $\left[-r_{l,t-1}+R^{\theta}_t\left(1+r_{l',t-1}\right)\right]\frac{1}{\pi_t\Omega^r_t}+\psi=0$, the same as A(18). When we use the combined constraint (3.33), the process is much less cumbersome, and we would get identical first-order conditions as A(16) and A(18).

B. Equilibrium Analysis

Proof of Proposition 1

From the first order condition A (1), we get

$$\eta_t^{\alpha} = U'(c_t;\alpha) \tag{B(1)}$$

Substitute B (1) into A (4), for $\forall t \in T$, we get

$$\ln(1 + r_{d,t}) = \ln\left(\frac{U'(c_t;\alpha)}{\beta_{\alpha} U'(c_{t+1};\alpha)}\right) + \ln(E_t \pi_{t+1}) - \ln(E_t R_{t+1}^{w}) \tag{B(2)}$$

Substitute B (1) into A(5), for $\forall t \in T$, we get

$$\ln(1 + r_{b,t}) = \ln\left(\frac{U'(c_t;\alpha)}{\beta_{\alpha} U'(c_{t+1};\alpha)}\right) + \ln(E_t \pi_{t+1}) \tag{B(3)}$$

Proof of Proposition 2 and 3

Combine A(4) and A(5), we obtain

$$1 + r_{b,t} = E_t R_{t+1}^{w} (1 + r_{d,t}) \tag{B(4)}$$

Combine A(12) and A(14), we get

$$(1 + r_{il,t}) = \frac{1}{E_t R_{t+1}^{r}} \left(1 + \frac{z^{w} c^{w}}{\eta_t^{w}}\right) \cdot (1 + r_{d,t}) \tag{B(5)}$$

Since $\left(1 + \frac{z^{w} c^{w}}{\eta_t^{w}}\right) > 1$. We get $(1 + r_{d,t}) < E_t R_{t+1}^{r} (1 + r_{il,t})$. In equilibrium, $0 < E_t R_{t+1}^{r} \leq 1$, thus $r_{d,t} < r_{il,t}$.

Combine A (16) and A (19), we get

$$1 + r_{il,t} = E_t[(1 - \delta_{t+1}^{r}) r_{l,t} + R_{t+1}^{\theta} \delta_{t+1}^{r} (1 + r_{l',t})] \tag{B(6)}$$

Assume $R_{t+1}^{\theta} > \frac{r_{l,t}}{1 + r_{l',t}}$. This is a reasonable assumption as our subsequent calibration shall support it, because if otherwise, the repayment rate of the firm would be extremely low, so the default penalty would substantially hurt his utility. If this assumption holds, the following conditions is satisfied:

$$1 - \delta_{t+1}^{r} < (1 - \delta_{t+1}^{r}) R_{t+1}^{\theta} \left(\frac{1 + r_{l',t}}{r_{l,t}}\right) \tag{B(7)}$$

Substitute B(7) into B(6), we get $E_t\left[(1-\delta^r_{t+1})r_{l,t}+R^\theta_{t+1}\delta^r_{t+1}\left(1+r_{l',t}\right)\right]<R^\theta_{t+1}(1+r_{l',t})$,

In other words,

$$1+r_{il,t}<E_tR^\theta_{t+1}(1+r_{l',t}) \qquad \text{B(8)}$$

Thus, $r_{il,t}<r_{l',t}$.

We thus obtain $r_{b,t}<r_{d,t}<r_{il,t}<r_{l',t}$. Typically, the interest rate of the corporate loans that haven't been paid back this period would be higher than that of the corporate loans that are paid back this period, otherwise firms would be encouraged to extend loan maturity, but in our model, the interest rate of long term corporate loans $r_{l,t}$ depends on the regulation on maturity mismatch, so there is no definite relationship between $r_{l',t}$ and $r_{l,t}$. We conclude

$$r_{b,t}<r_{d,t}<r_{il,t}<r_{l',t} \ .$$

Proof of Proposition 4

Supposing that $v^\theta_t, v^w_t, v^r_t>0$ holds, then three first order conditions, A (10), A (13) and A (17) yield

$$u'(\theta,t)=\frac{\lambda^\theta\delta^\theta_t u^\theta_{t-1}(1+r_{l',t-1})(1-v^\theta_t)}{\pi_t}$$
$$u'(w,t)=\frac{\lambda^w u^w_{t-1}(1+r_{d,t-1})(1-v^w_t)}{\pi_t}$$
$$u'(r,t)=\frac{\lambda^r u^r_{t-1}(1+r_{il,t-1})(1-v^r_t)}{\pi_t}$$

Proof of Proposition 5

For the firms: from A (8) we have

$$1=\frac{\lambda_\theta\delta^\theta_t u^\theta_{t-1}(1+r_{l',t-1})(1-v^\theta_t)}{\pi_t}$$
$$\frac{\partial v^\theta_t}{\partial\delta^\theta_t}>0$$

For the retail bank: from A (17), we have

$$\left\{\frac{1}{\pi_t}\left[(1-\delta_t^r)L_{t-1}r_{l,t-1}+R_t^\theta L_{t-1}\delta_t^r\left(1+r_{l',t-1}\right)-v_t^r u_{t-1}^r\left(1+r_{il,t-1}\right)\right]\right\}^{-\sigma^r}$$
$$=\frac{\lambda_r u_{t-1}^r\left(1+r_{il,t-1}\right)(1-v_t^r)}{\pi_t}$$
$$\left(-\sigma^r(\Omega_t^r)^{-\sigma^r-1}-\lambda_r\right)u_{t-1}^r\left(1+r_{il,t-1}\right)dv_t^r$$
$$=\sigma^r(\Omega_t^r)^{-\sigma^r-1}\left[L_{t-1}r_{l,t-1}-R_t^\theta L_{t-1}\left(1+r_{l',t-1}\right)\right]d\delta_t^r$$

Note that $\left(-\sigma^r(\Omega_t^r)^{-\sigma^r-1}-\lambda_r\right)u_{t-1}^r\left(1+r_{il,t-1}\right)<0$ and $\left[L_{t-1}r_{l,t-1}-R_t^\theta L_{t-1}\left(1+r_{l',t-1}\right)\right]<0$ according to A(18). Thus, $\frac{\partial v_t^r}{\partial \delta_t^r}>0$.

For the wholesale bank, there's no direct relationship between maturity mismatch and the wholesale bank's default rate. However, although this is not the focus of our paper, we can show that an implementation of LCR would lead to a decrease of the wholesale bank's default rate. The implementation of LCR leads to an increase of safe assets. When safe asset increases, wholesale bank's and retail bank's profit decreases, and this causes next period repayment to increase, which implies a fall in default rate of the wholesale bank and of the retail bank.

Note that, $\Omega_{t+1}^w=\frac{1}{\pi_{t+1}}\left[(1+r_{b,t})B_t^w+W_t\left(1+r_{il,t}\right)R_{t+1}^r-v_{t+1}^w\left(1+r_{d,t}\right)u_t^w\right]$

$$c_t^w=\frac{B_t^w}{B_t^w+W_t}$$
$$\frac{\partial\Omega_{t+1}^w}{\partial c_t^w}=\frac{1+r_{b,t}}{\pi_{t+1}}\frac{\partial B_t^w}{\partial c_t^w}+\frac{\left(1+r_{il,t}\right)R_{t+1}^r}{\pi_{t+1}}\frac{\partial W_t}{\partial c_t^w}$$
$$\frac{\partial\Omega_{t+1}^w}{\partial c_t^w}=\frac{(1+r_{b,t})(B_t^w+W_t)}{\pi_{t+1}(1-c_t^w)}-\frac{\left(1+r_{il,t}\right)R_{t+1}^r(B_t^w+W_t)}{\pi_{t+1}c_t^w}$$

Assume $\frac{(1+r_{b,t})(B_t^w+W_t)}{\pi_{t+1}(1-c_t^w)}<\frac{\left(1+r_{il,t}\right)R_{t+1}^r(B_t^w+W_t)}{\pi_{t+1}c_t^w}$[12]. Thus,

$$\frac{\partial\Omega_{t+1}^w}{\partial c_t^w}<0$$

And from the profit equation, we know

$$\frac{\partial v_{t+1}^w}{\partial\Omega_{w,t+1}}<0$$

So when c_t^w increases, i.e. a contractionary shock in LCR, profit decreases, and this causes next period repayment to increase, which implies a fall in default rate of the wholesale

[12] This is more of a calibration issue and it's obvious to see that it's a reasonable assumption as well, because otherwise the wholesale bank's liquidity ratio would be substantially large.

bank.

Furthermore, $\frac{\partial c_t^w}{\partial z^w} > 0$, and this means the implementation of NSFR leads to an increase of safe assets. The retail bank's case can be shown in a similar fashion.

C. Bayesian Estimation

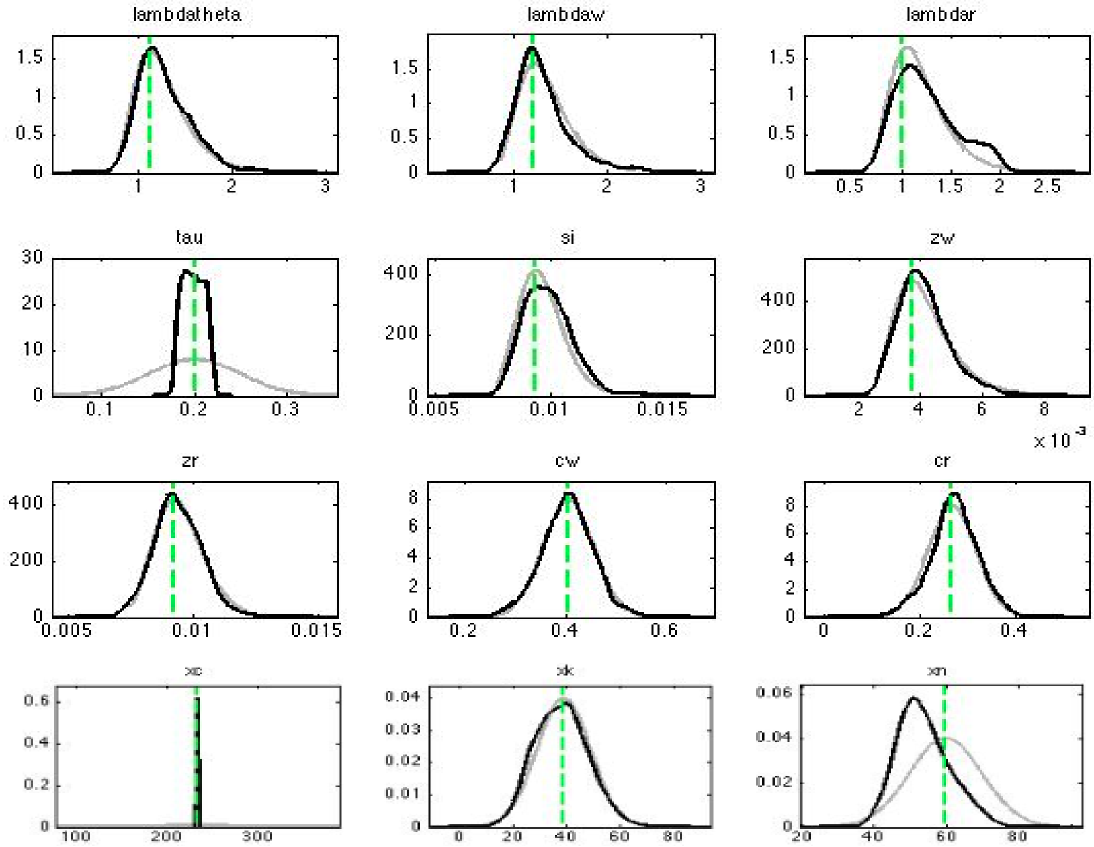


Figure C Prior and posterior distributions of selected parameters

Table C Endogenous variables in steady states

Variable	Value	Variable	Value
q_k	20.3044991704311	$r_{l'}$	0.0159
p_k	4.79334734471087	r_l	0.02
q_n	473.416354295645	η^α	1.00005196
p_n	0.26432144218762	η^θ	1.00005196
B^α	59.3228295218408	η	0.0041
D	296.614147609204	η^w	1.00005196
u^θ	222.460610706903	η^r	1.00005196
B^w	118.645659043682	Ω^θ	8.65728983524099
W	177.968488565522	Ω^w	0.743544949969022
u^w	296.614147609204	Ω^r	0.9977
B^r	74.153536902301	C	234.181003180944
L	222.460610706903	y	234.181003180944
u^r	296.614147609204	b_k	20.304499170431100
M	118.645659043682	b_n	473.416354295645
B	252.122025467823	k^α	240.884857682967
δ^θ	0.65	k^θ	101.522495852156
δ^r	0.65	R^θ	0.9946
v^θ	0.9946	R^w	0.997529060664989
v^w	0.997529060664989	R^r	0.9972
v^r	0.9972	π	1
r_b	0.00371374084111209		
r_d	0.0062		
r_{il}	0.0107217201036538		

D. Quantitative Analysis via IRFs

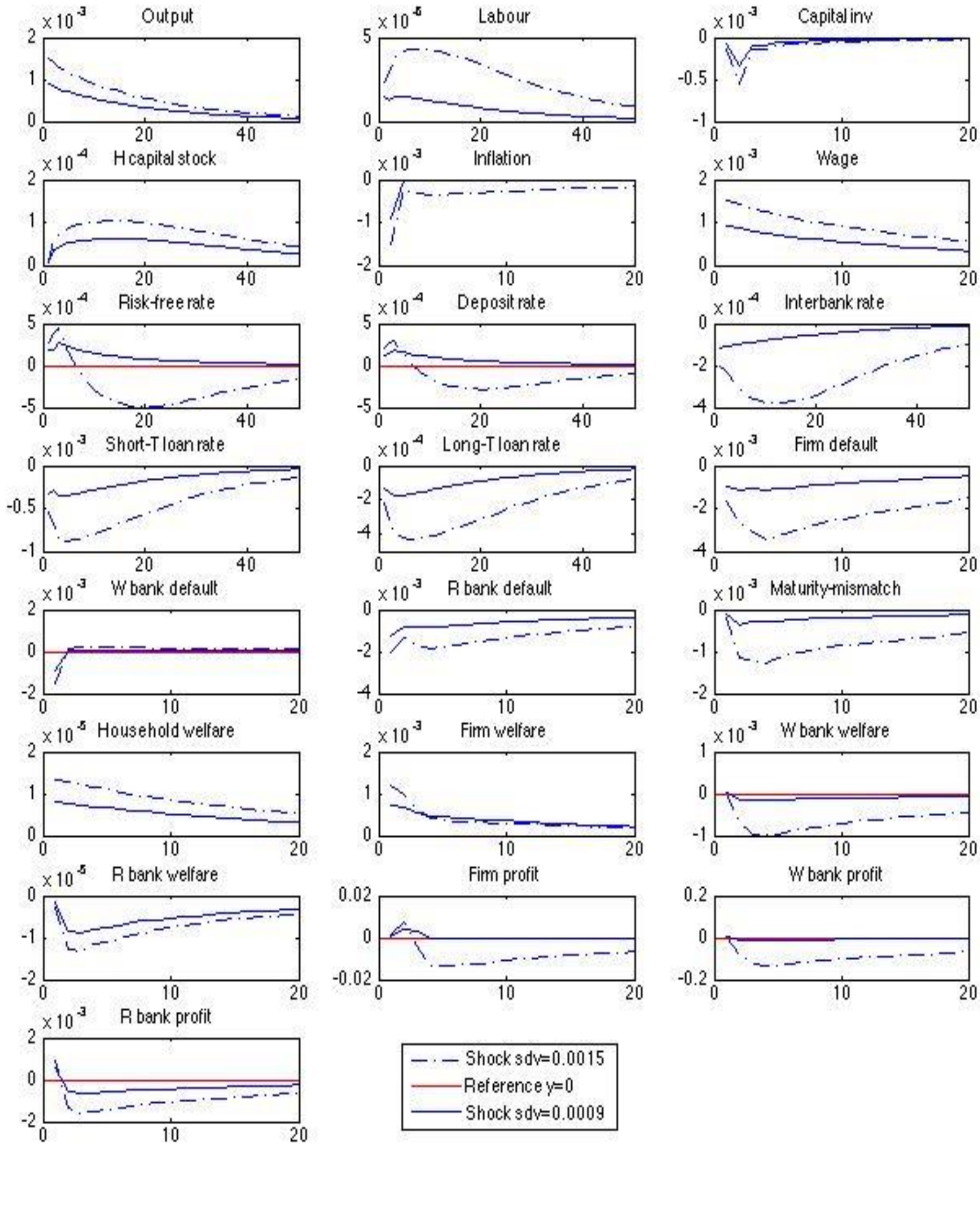


Figure D-1: Responses of major macroeconomic variables to one-time positive technology shock

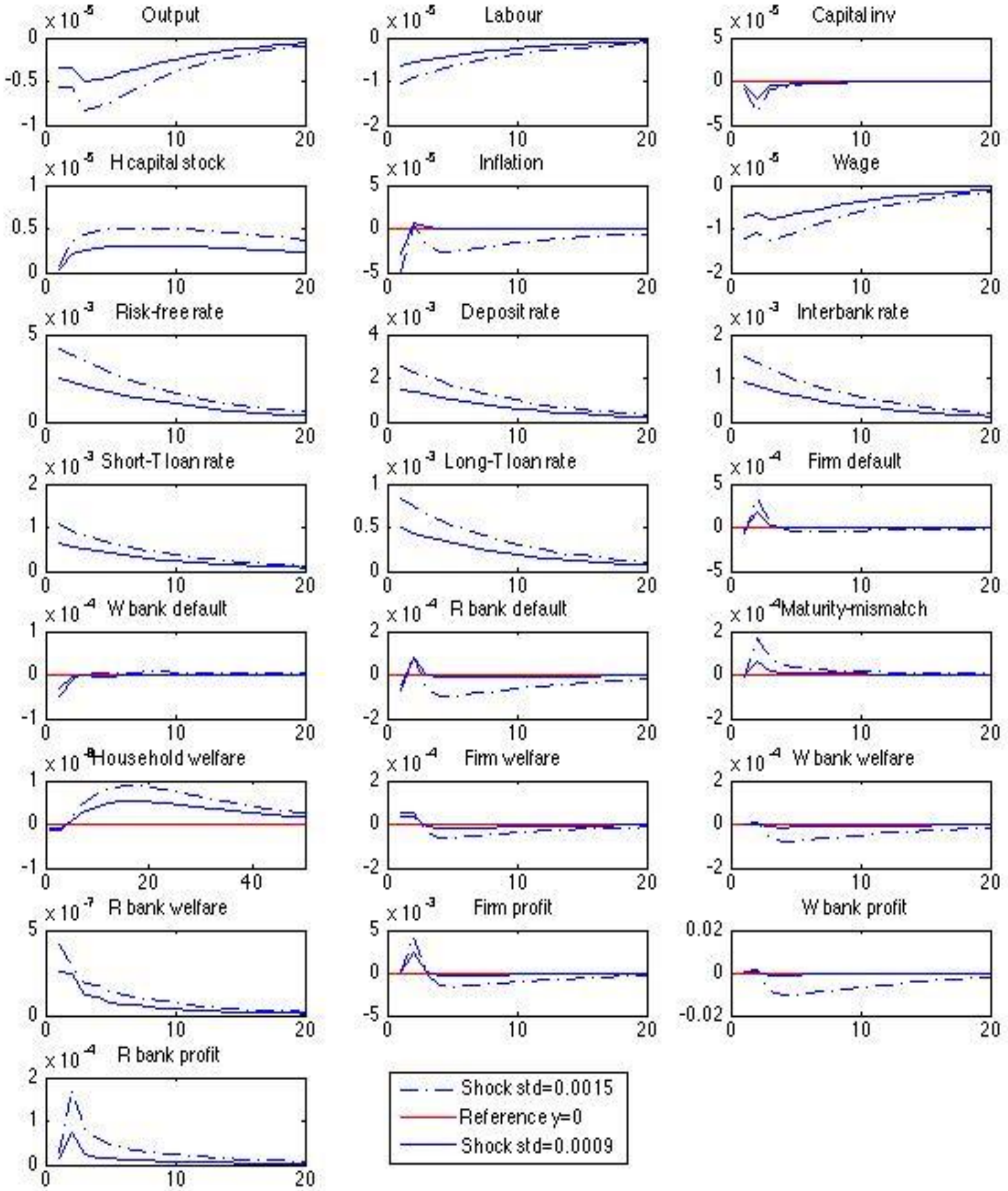


Figure D-2: Responses to one-time stringent monetary shock

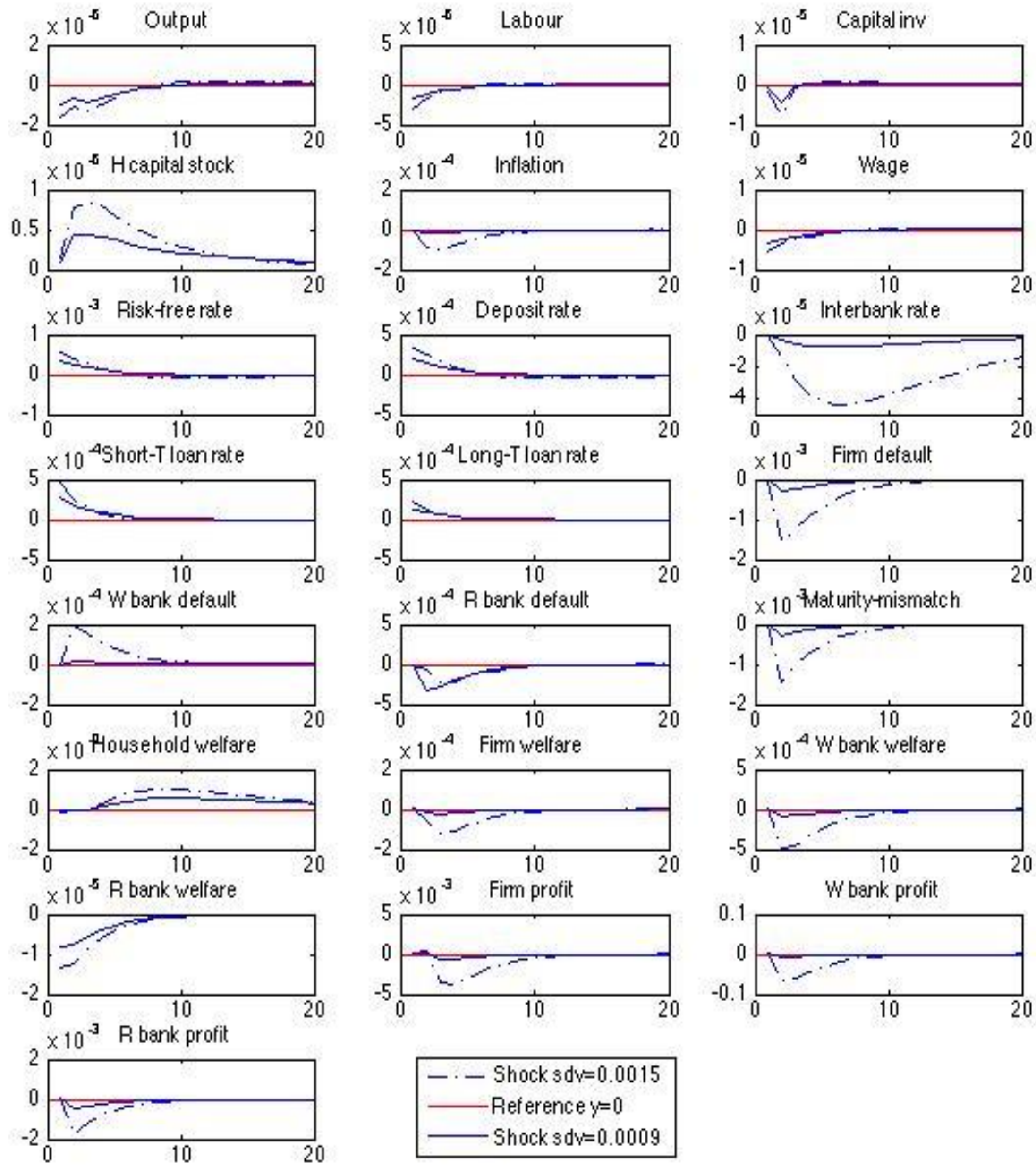


Figure D-3: Responses to one-time stringent macro-prudential policy (NSFR) shock

E. Welfare Analysis via IRFs across Regimes

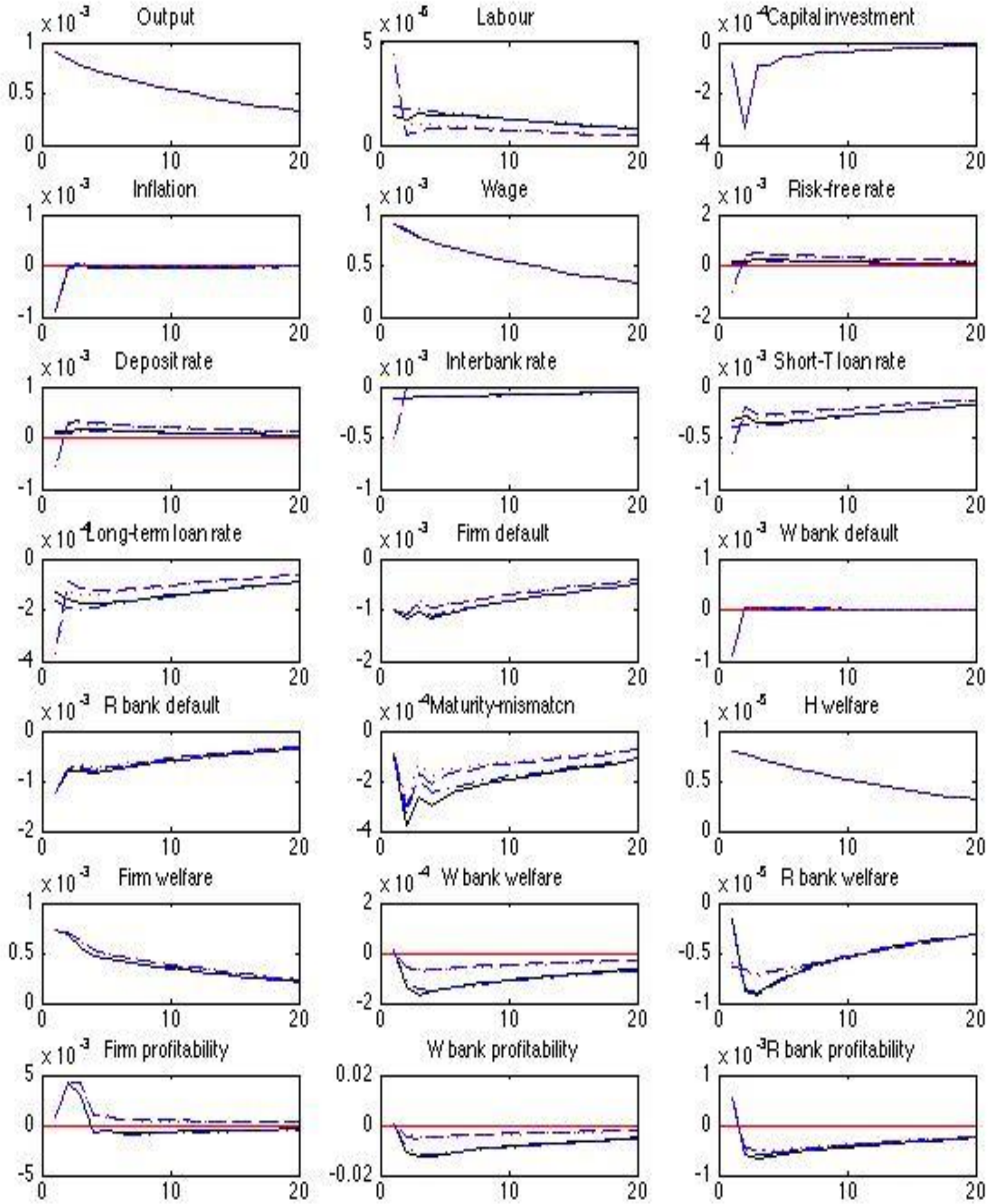
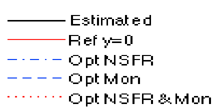


Figure E-1: Responses to one-time positive technology shock across different policy regimes

$\epsilon_{\alpha,1} = 0.0009$ given that $\epsilon_{\alpha,t} = 0$ for $\forall t \geq 2$



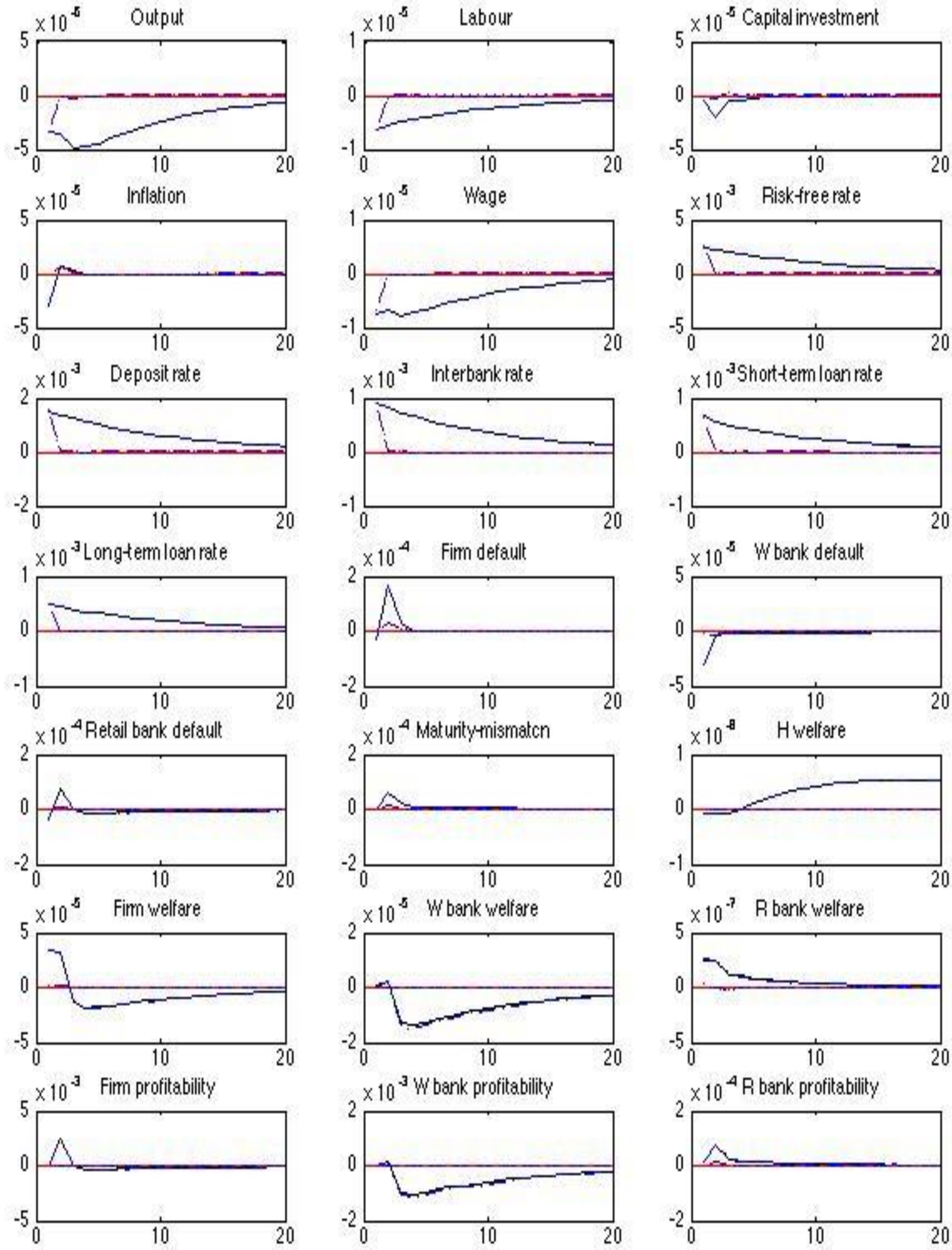


Figure E-2: Responses to one-time stringent monetary shock across different policy regimes $\epsilon_{r,1} = 0.0009$ given that $\epsilon_{r,t} = 0$ for $\forall t \geq 2$

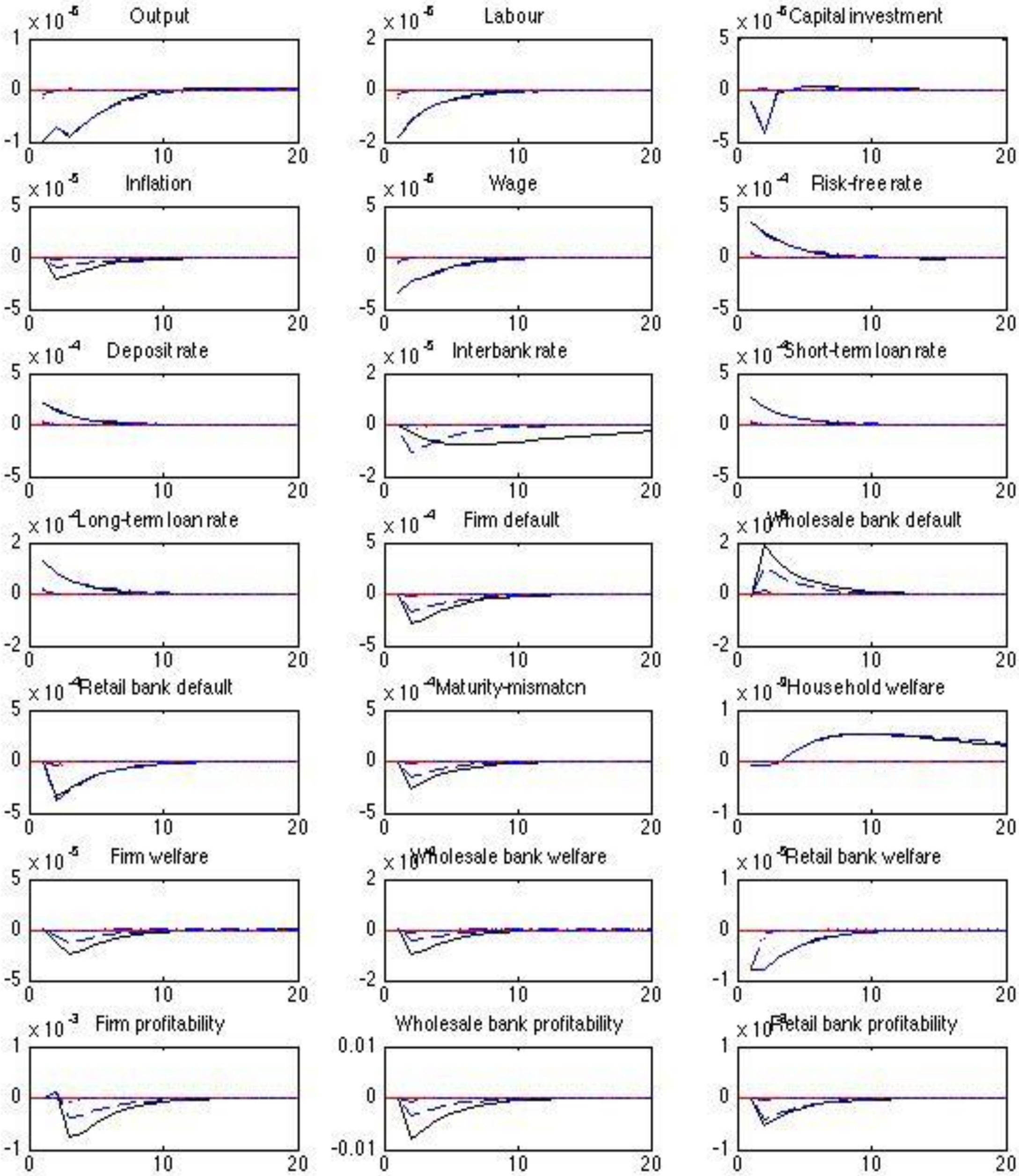


Figure E-3: Responses to one-time stringent macro-prudential policy (NSFR) shock across different policy regimes $\epsilon_{\delta,1} = 0.0009$ given that $\epsilon_{\delta,t} = 0$ for $\forall t \geq 2$