Sheffield Hallam University

UK monetary and fiscal policy since the great recession - an evaluation

VO PHUONG, Mai Le, MEENAGH, David, MINFORD, Patrick and WANG, Ziqing

Available from Sheffield Hallam University Research Archive (SHURA) at:

https://shura.shu.ac.uk/34162/

This document is the Accepted Version [AM]

Citation:

VO PHUONG, Mai Le, MEENAGH, David, MINFORD, Patrick and WANG, Ziqing (2024). UK monetary and fiscal policy since the great recession - an evaluation. Applied Economics. [Article]

Copyright and re-use policy

See http://shura.shu.ac.uk/information.html

Sheffield Hallam University Research Archive
http://shura.shu.ac.uk

UK monetary and fiscal policy since the Great Recession- an evaluation

Vo Phuong Mai Le[1], David Meenagh[1], Patrick Minford[1], Ziqing Wang[2,3]

[1*]Cardiff Business School, Cardiff University, Cardiff, United Kingdom.
[2]Sheffield Hallam University, Sheffield, United Kingdom .
[3]Corresponding author – Ziqing.Wang@shu.ac.uk.

Abstract

This paper quantifies the economic impacts of the Bank of England's quantitative easing (QE) policy, implemented in response to the global financial crisis. Using an open economy Dynamic Stochastic General Equilibrium (DSGE) model, we demonstrate that monetary policy can remain effective even when nominal interest rates have reached the zero lower bound. Our analysis shows that QE measures have significantly influenced economic stabilization. We estimate and test the model using the indirect inference method, and our simulations indicate that a nominal GDP targeting rule implemented through money supply could be the most effective monetary policy regime. Additionally, our findings suggest that a robust, monetary active regime with nominal GDP targeting could significantly enhance economic stabilization efforts.

Keywords: Quantitative easing, Financial friction, SOE-DSGE, Indirect inference, Zero bound

JEL Classification: E44 , E52 , E58 , C51

1 Introduction

[1] The onset of the Global Financial Crisis (GFC) in August 2007, which was further exacerbated by the collapse of Lehman Brothers in September 2008, triggered a severe recession in several major economies. The UK experienced a sharp contraction in output of around 20% on an annualized basis in the first quarter of 2009, coupled

[1]We are grateful to Dr. Zheyi Zhu for his assistance and advice in the use of Cardiff University's Hawk supercomputer.

with an unprecedented increase in the unemployment rate to 7.6%. In response, the Bank of England (BoE) pursued expansionary monetary policies to boost demand, aggressively lowering the interest rate to its effective lower bound. Specifically, the Monetary Policy Committee of the BoE reduced the interest rate from 5% to 0.5% in 2009, followed by a further cut to 0.25% by the autumn of 2016, when the short-term rate became constrained by the zero lower bound. Successively, It implemented unconventional monetary polices , including 3 rounds of quantitative easing which involved injecting money into the economy through large-scale asset .

This paper aims to identify the causes of the UK GFC and draw policy implications, encompassing monetary, regulatory, and fiscal measures. To this end, we employ a Dynamic Stochastic General Equilibrium (DSGE) model of the UK economy, which we estimate and test using an indirect inference method against empirical behavior observed over the relevant period. This method confers robustness on the model's small sample performance, as it is fully identified by structural constraints. In particularly, we place the banking sector at the heart of monetary transmission, embodying the key financial friction in the economy. We do so because it seems clear that this crisis primarily arose in the banking system, often being referred to as a banking crisis, and that both monetary policy and bank regulation had major effects on the behavior of bank credit. Our model adopts the financial accelerator approach of Bernanke et al. (1999) and embeds in it the effects of banking regulation and also adds a collateral element; QE, through the additional liquidity it injects, acts to reduce the cost of this collateral and lower the cost of credit. We extended Le et al. (2016)'s model which successfully matched US data behaviour to incorporate the open economy elements.

Our model is closely related to Lyu et al. (2023), who had a similar DSGE structure to demonstrate that a monetary regime using a counteractive M0 rule can stabilize the UK economy. However, their study did not explore the potential benefits of alternative monetary policies, nor did it examine the interactions between fiscal and monetary policy. Our study aims to provide a more comprehensive analysis by incorporating both fiscal and monetary policy factors to better understand their combined effects on economic stability.

The rest of the paper is structured as follows. Section 2 sets out the model. Section 3 introduces the indirect inference method and estimates and tests the model. In Section 4, we set out the empirical findings and discuss the causes of the crisis. Section 5 considers the implications for policy; we simulate the model with alternative monetary, regulative and fiscal policies and analyse how they affect economic stability and welfare. Section 6 concludes.

2 Literature Review

There is an extensive literature, both theoretical and empirical, on the crisis episode and the effects of QE within it. Here we examine some key findings of this literature.

First, we review SVAR studies for the US and UK. Walentin (2014) finds that exogenous shocks to US mortgage spreads have big effects on house prices, residential investment, consumption and GDP. Thus unconventional monetary policy in the form of asset purchases in mortgage markets can affect the mortgage spread, and it also has big effects on house prices and GDP. He finds that if QE1 had a 150 basis points effect on the mortgage spread (as in Hancock and Passmore, 2011), then it would have raised GDP at the peak by 3.8% and house prices by 5.1%. Using a time-varying parameter SVAR Baumeister and Benati (2013) found that the US and UK QE1 reduced big drops in GDP and prices by narrowing term spreads. Using the estimate of a 60 basis points drop in the US term spreads from Gagnon et al. (2011) they find that US QE1 lowered the ten-year Treasury yield by 58 basis points, stopped inflation from reaching a low of -1% and output from reaching a trough of -10%. With an assumption of a 50 basis points drop in term spreads in the UK, QE1 would have prevented a fall in inflation from reaching -4% and output from a trough of -12%. Applying various time-varying VARs to the UK data, Kapetanios et al. (2012) found that the peak effects of QE1 were +1.5% on real GDP and +1.25% on CPI inflation.

Next we review a variety of theoretical models investigating effects of QE on the economy. The first group derives QE's effectiveness via an assumption of exogenous participation constraints in financial markets, so QE can have real effects via its impact on the yield curve. Following the theoretical work by Vayanos and Vila (2009), and other empirical investigations following it (e.g. Hamilton and Wu, 2012), Chen et al. (2012) set up a medium size DSGE model with segmented asset markets, where some agents trade in both long-term and short-term bonds, subject to a transaction cost, which is a diminishing function of the ratio of central bank holdings of long-term to short- term bonds, while other agents can only trade in long-term bonds. The transaction cost ensures there is a term premium in the no-arbitrage asset pricing condition; central bank purchases of long-term bonds would reduce this term premium to produce real macroeconomic effects. They estimate the model with Bayesian methods for US postwar data. They find that US QE2, a $600 billion purchase of long-term government bonds, causes GDP to rise by 0.13%.

Gertler and Karadi (2011, 2013), Gertler and Kiyotaki (2010) and Sims and Wu (2021) assume that the QE effects work through the binding leverage constraints on intermediaries. The idea here is that banks who intermediate between households and non-financial firms can abscond with funds. To eliminate this incentive, there is a binding incentive constraint, which also means a binding leverage constraint. Limits to arbitrage create a wedge/premium between the expected return on capital and risk-free debt, which is inversely related to banks' net worth. In these models, when leverage constraints bind and financial shocks raise the external finance premium, government credit policy can act countercyclically by influencing net worth. In Gertler and Karadi (2011), QE acts as direct financial intermediation by the central bank to offset disruption to private financial intermediation. Although the central bank is less efficient than private intermediaries, the central bank is not subject to the leverage constraint and can issue risk free debt to raise funds elastically from households to fund non-financial firms. When the constraint on private intermediation tightens during a crisis, QE can act countercyclically. Gertler and Karadi (2013) aim to develop a unified framework to analyse all large scale asset purchases by extending Gertler and Karadi (2011) with an additional assumption that banks can intermediate the funding of long-term government bonds as well as the funding of non-financial firms, thus the interest spread depends on the long-term bonds fraction of intermedi- aries' assets. Also, the central bank can conduct monetary policy by either adjusting the short-term interest rate or by purchasing long-term government bonds and private securities. They find that US QE2 would have raised GDP by around 1%. Sims and Wu (2019) extend Gertler and Karadi (2013) to include the central bank's balance sheet with interest-bearing reserves, which financial intermediaries are required to hold and cannot be stolen. The central bank can hold either private or government bonds, which are financed via the creation of reserves. The model assumes that firms issue long-term bonds to finance investments and financial intermediaries hold long-term bonds and reserves. Market clearing requires that bonds issued by firms and debt issued by the government must be held by the central bank or financial intermediaries. When intermediaries are constrained via the costly enforcement problem, then QE, as central bank purchases of long-term bonds via creation of interest-bearing reserves, does not crowd out intermediary bond purchases so that the total demand for long-term bonds increases, causing higher bond prices, easing the constraint and elevating aggregate demand. They find that US QE can account for 2/3 of the observed decline in the shadow Federal Funds rate.

Chen et al. (2012) and Gertler and Karadi (2013) also find that a credible central bank commitment to hold short-term interest rates at zero generates most of the GDP effects. This commitment works via a signalling channel, i.e. by accumulating a large balance sheet through long-term bond purchases, it signals lower short-term policy rates in the future and thereby reduces current long rates. Bhattarai et al. (2019) used a model without financial frictions or participation constraints to study time-consistent discretionary policy and how the maturity composition of government debt affects optimal future interest rates. Their calibration matches Krishnamurthy and Vissing-Jorgensen (2011)'s event-study estimates of the signalling effects of US QE2 on long-term yields, expected inflation, inflation and output during the Great Recession. They find that QE2 increases output by 1.6% and inflation by 1.4% on impact.

Although this is not an exhaustive list of available studies, we observe that most of the DSGE studies in the literature focus on US experience with QE and many quantitative analyses are based on calibration or Bayesian estimation. These studies produce a wide range of implied results for QE policy. However, none was tested and statistically evaluated. Our model is closely related to the strand of the literature based on the leverage constraint on intermediaries. Its idea is similar to Gertler and Kiyotaki (2011) and Gertler and Karadi (2013) - there is a leverage constraint, but instead of QE working to relax the intermediaries' constraint, we assume that QE eases firms' constraints. We test it against UK data for the post-crisis period to establish empirical conclusions about the effects of monetary policy and regulation on a major open economy.

3 Model Set-up

3.1 Household Sector

The representative household maximizes its utility function, which affects their choices of consumption (C_t) and labor (L_t). The utility function reflects both the intertemporal trade-off in consumption and the disutility from labor. The utility function is mathematically represented as:

$$U = \max E_t \sum_{s=0}^{\infty} \beta^s \left[\frac{(C_{t+s} - \lambda C_{t+s-1})^{1-\sigma_c}}{1-\sigma_c} \right] \exp\left(\frac{\sigma_c - 1}{1+\sigma_l} L_{t+s}^{1+\sigma_l} \right) \tag{1}$$

where σ_c is the coefficient of relative risk aversion, σ_l is the labor supply elasticity, and λ represents habit formation in consumption, influencing the utility derived from current consumption relative to past consumption.

The household budget constraint ensures that total expenditures, including consumption C_t, domestic bond holdings B_t, and foreign bond holdings B_t^f, do not exceed income sources. These income sources consist of the previous period's bond holdings adjusted for current prices, wages W_t, and taxes T_t. Domestic and foreign interest rates are denoted as R_t and R_{Ft}, respectively. S_t is the nominal exchange rate, Q_t is the real exchange rate, and P_t is the price level. Additionally, the intertemporal budget constraint incorporates a preference shock e_{bt}, which influences consumption decisions by modifying the perceived utility from spending:

$$C_t + \frac{B_t}{R_t P_t e_{bt}} + \frac{S_t B_t^f}{R_{Ft} P_t e_{bt}} \leq \frac{B_{t-1}}{P_t} + \frac{S_t B_{t-1}^f}{P_t} + \frac{D_t}{P_t} + \frac{W_t L_t}{P_t} + T_t \tag{2}$$

The Euler equation for consumption derives from optimizing the intertemporal consumption choice subject to the budget constraint, illustrating how expected future consumption, adjusted for preference shocks and interest rates, influences current consumption:

$$[C_t - hC_{t-1}]^{-\sigma} \exp\left(\frac{\sigma_l - 1}{1+\sigma_l} L_t^{1+\sigma_l} \right) = E_t \left\{ [C_{t+1} - hC_t]^{-\sigma} \exp\left(\frac{\sigma_l - 1}{1+\sigma_l} L_{t+1}^{1+\sigma_l} \right) \frac{P_t}{P_{t+1}} \beta R_t \right\} \tag{3}$$

This equation states that the marginal rate of substitution between consumption in two consecutive periods, adjusted for inflation and the nominal interest rate, should equal one, reflecting optimal intertemporal allocation of consumption.

The uncovered interest parity (UIP) condition, derived from the FOCs for domestic and foreign bonds, equates expected changes in the exchange rate to the differential between domestic and foreign interest rates:

$$E_t \left[\frac{S_{t+1}}{S_t} \right] = \frac{R_t}{R_t^f} \tag{4}$$

3.2 Foreign Sector

According to a single-industry version of Armington's (1969) model, the total consumption for each household (C_t) is differentiated by the place of production. Specifically, we distinguish between domestically produced products (C_t^d) and imported goods (C_t^f). The utility function for aggregated consumption can be represented via the constant elasticity of substitution (CES) index:

$$C_t = \left[\omega(C_t^d)^{-\rho} + (1-\omega)\zeta_t(C_t^f)^{-\rho}\right]^{-\frac{1}{\rho}} \tag{5}$$

We assume that domestic consumers have a fixed preference bias towards domestic products, measured by ω where $0 < \omega < 1$. ρ is related to the elasticity of substitution between domestic and foreign goods' variety, which is constant at $\sigma = \frac{1}{1+\rho}$. ζ_t represents the preference error in the demand for imported goods. The total expenditure on consumption is defined as $C_t = p_t^d C_t^d + Q_t C_t^f$. p_t^d is the ratio of the domestic price relative to the general price level (P_t), defined as $p_t^d = \frac{P_t^d}{P_t}$. By setting up the Lagrangian function, we can derive the demand for imports:

$$\hat{C}_t^f = \left[(1-\omega)\hat{\zeta}_t\right]^{\sigma}(\hat{Q}_t)^{-\sigma}\hat{C}_t \tag{6}$$

Symmetrically, the export equation is:

$$(\hat{C}_t^f)^* = \left[(1-\omega_f)\hat{\zeta}_t^*\right]^{\sigma_f}(\hat{Q}_t^*)^{-\sigma_f}\hat{C}_t^* \tag{7}$$

where $(\hat{C}_t^d)^*$ and $(\hat{C}_t^f)^*$ are the foreign demand for their domestic products and imported goods, respectively. Similarly, ω_f is a foreign consumer's home bias, $\hat{C}_t^*$ is total consumption, σ_f is the foreign country's elasticity of substitution between domestic and imported goods, and $\hat{\zeta}_t^*$ represents the foreign random preference error in the demand for imports.

Assuming no capital controls, the balance of payments constraint links the net foreign assets position (NFA) with the trade balance:

$$Q_t \cdot \frac{B_t^f}{R_t^f} - Q_t \cdot B_{t-1}^f = p_t^d \cdot EX_t - Q_t \cdot IM_t \tag{8}$$

The equation signifies that changes in Net Foreign Assets (NFA), measured in foreign currency, depend on the difference between exports EX_t and imports IM_t. Exports are measured in domestic currency and adjusted by the domestic price level p_t^d, while imports are measured in domestic currency, scaled by the real exchange rate Q_t. This identity highlights how fluctuations in trade flows influence a country's external financial position, considering the effects of exchange rate movements and interest rate differentials.

3.3 Labor Intermediaries and Hybrid Wage-Setting

Smet and Wouters (2007) describe labor markets as comprising two key actors: labor unions and labor packers. Households supply homogeneous labor to the labor union, which then allocates and differentiates labor services before selling them to labor packers. The labor packers then aggregate the labor services from the labor union using an aggregator proposed by Kimball (1995) and provide them to intermediate goods producers for production.

$$\max_{L_t, L_t(i)} \left(W_t L_t - \int_0^1 W_t(i) L_t(i)\, di \right) \tag{9}$$

Subject to the Kimball aggregator constraint:

$$\left(\int_0^1 H\left(\frac{L_t(i)}{L_t} \right) di \right)^{\lambda_{w,t}} = 1 \tag{10}$$

where the function $H\left(\frac{L_t(i)}{L_t}\right)$ is defined as:

$$H\left(\frac{L_t(i)}{L_t} \right) = \frac{1}{1+\lambda_{w,t}} \left(\frac{L_t(i)}{L_t} \right)^{\frac{1}{1+\lambda_{w,t}}} \tag{11}$$

W_t is the wage of composite labor; $W_t(i)$ is the wage of differentiated labor service i; L_t is the composite labor; $L_t(i)$ is the differentiated labor service; $\lambda_{w,t}$ is the parameter that measures shocks to the aggregator function, affecting demand and mark-up. By FOC, the optimal demand for labor from labor unions is:

$$L_t(i) = \left(\frac{W_t(i)}{W_t} \right)^{-\frac{1+\lambda_{w,t}}{\lambda_{w,t}}} L_t \tag{12}$$

The labor unions work as an intermediate between the household and the labor packer. Under the Calvo pricing indexation, part of labor unions can adjust their price based on the following optimization problem:

$$\max E_t \sum_{s=0}^{\infty} \beta^s \xi_p^s \frac{\Xi_{t+s} P_t}{\Xi_t P_{t+s}} L_{t+s}(i) [\widetilde{W_t(i)} (\Pi^w_{t,t+s}) - W_t^h] \tag{13}$$

where $\Pi^w_{t,t+s} = \Pi^s_{k=1} (\frac{\pi_{t+k-1}}{\pi_t})^{l_w}$. Subject to the labor demand function, the optimal wage will satisfy the following condition:

$$\sum_{s=0}^{\infty} \beta^s \xi_p^s \frac{\Xi_{t+s} P_t}{\Xi_t P_{t+s}} \left[(1-\omega^w) L_{t+s} W_t(i)^{-\omega^w} W_t^{\omega^w} + \omega^w L_{t+s} W_{t+s}^h W_t(i)^{-\omega^w - 1} W_t^{\omega^w} \right] = 0 \tag{14}$$

where $\omega^w = -\frac{1+\lambda^w_{p,t}}{\lambda^w_{p,t}}$. Then the law of motion of the aggregate wage is:

$$W_t = [\xi_w (W(i)_{t-1} (\frac{\pi_{t-1}}{\pi_t})^{l_w})^{\frac{1}{\lambda_{w,t}}} + (1-\xi_w)(\widetilde{W_t(i)})^{\frac{1}{\lambda_{w,t}}}]^{\lambda_{w,t}} \tag{15}$$

Smet and Wouters (2007) adopt a New Keynesian (NK) model in which prices and wages are sticky due to Calvo-type pricing in both goods and labor markets. However, there is significant disagreement over the extent of nominal rigidity, which is crucial as it determines the short-run non-neutrality of monetary policy and the effectiveness of monetary interventions for stabilizing the economy. Le et al. (2011) test both the NK and a New Classical (NC) version of the model using indirect inference on US postwar data, and find that both models are strongly rejected as the NK model generates too much nominal rigidity while the NC model generates too little. The authors also considered a weighted model that allowed for nominal rigidity in some parts of the economy but not others, finding that it provided the appropriate amount of nominal rigidity for the US economy. We follow Le et al. (2012) to build a hybrid wage model. We assume a fixed fraction (ν^w) of labor is from imperfect competitive market and the remaining $(1-\nu^w)$ is from competitive market. If the wage is perfectly flexible and mark up equals zero, the real wage would equal the marginal substitution rate between consumption and leisure. The hybrid wage which will be passed to labor packers is then defined as:

$$W_t^{Hybrid} = \nu_w W_t + (1-\nu_w) W_t^{NC} \tag{16}$$

3.4 Final Goods Producer and Hybrid Price-Setting

Final goods producers package the intermediate goods as final products using a Kimball (1995) aggregator:

$$Y_t = \left(\int_0^1 H\left(\frac{Y_t(i)}{Y_t}\right) di \right)^{\lambda_{p,t}} \quad \text{where} \quad H\left(\frac{Y_t(i)}{Y_t}\right) = \frac{1}{1+\lambda_{p,t}} \left(\frac{Y_t(i)}{Y_t}\right)^{\frac{1}{1+\lambda_{p,t}}} \tag{17}$$

To generate the optimal demand for intermediate goods, they maximize the profit function with the constraint of final goods production:

$$\max_{Y_t, Y_t(i)} \left(P_t Y_t - \int_0^1 P_t(i) Y_t(i)\, di \right) \quad \text{s.t.} \quad Y_t = \left(\int_0^1 H\left(\frac{Y_t(i)}{Y_t}\right) di \right)^{\lambda_{p,t}} \tag{18}$$

Where P_t and $P_t(i)$ are the prices of final goods and intermediate goods, respectively. Y_t and $Y_t(i)$ represent the final goods and intermediate goods, respectively. $\lambda_{p,t}$ is an exogenous shock that causes changes in the elasticity of demand and price markup. It follows an AR(1) process as: $\ln(\lambda_{p,t}) = \rho_p \ln(\lambda_{p,t-1}) + \eta_p$. FOC gives the optimal demand for intermediate goods input, which depends negatively on their relative price:

$$Y_t(i) = Y_t \left(\frac{P_t(i)}{P_t}\right)^{-(1+\lambda_{p,t})} \tag{19}$$

Finally, solving for $P_t(i)$ using the profit maximization problem, we get:

$$P_t(i) = P_t \left(\frac{Y_t}{Y_t(i)}\right)^{\frac{\lambda_{p,t}}{1+\lambda_{p,t}}} \tag{20}$$

In an environment of perfect competition, producers of final goods are price takers. They evaluate intermediate goods, and we assume, following Le et al. (2012), that the final output consists of intermediate goods from a monopoly market (ν_p) and perfectly competitive markets (1-ν_p). In a competitive market with zero price markup, intermediate goods are priced at their marginal cost(MC). Thus, the final goods equation for this hybrid market is as follows:

$$P_t^{Hybrid} = \nu_p P_t + (1 - \nu_p) P_t^{NC} \tag{21}$$

$$P(i)_t^{NC} = MC_t \tag{22}$$

3.5 Intermediate Goods Producer

To incorporate the concept of financial friction, we modify the DSGE framework in Smets and Wouters (2007) by drawing on the BGG model. In our modified framework, entrepreneurs act as the intermediate goods producers. They hire labor and purchase installed capital using constant return to scale technology to produce intermediate goods ($Y_t(i)$). Additionally, entrepreneurs purchase capital from capital producers using externally financed funds and net worth. The intermediate goods are produced via a Cobb-Douglas production function with capital services $K_t^s(i)$ and labor input $L_t(i)$ as inputs.

$$Y_t(i) = K_t^s(i)^\alpha [\gamma^t L_t(i)]^{1-\alpha} \varepsilon_t^\alpha - \gamma^t \phi \tag{23}$$

where α represents the share of capital in the production function, ϕ stands for the fixed cost contributing to real rigidity, γ is the labor augmenting deterministic growth rate, and ε_t^α signifies the total factor productivity shock, which is assumed to exhibit non-stationary behavior. $K_t^s(i)$ is defined as

$$K_t^s(i) = Z_t(i) K_{t-1}(i) \tag{24}$$

$Z_t(i)$ is the capital utilisation rate. The optimal capital utilization rate is found by solving the maximizing problem. The income from buying capital services is $Rrental_t Z_t(i) K_{t-1}(i)$ and the cost of changing capital utilisation is $a(Z_t(i))K_{t-1}(i)$, where $a(Z_t(i))$is the adjustment cost of capital utilisation.

$$\max_{Z_t(i)} (Rrental_t Z_t(i) K_{t-1}(i) - a(Z_t(i)) K_{t-1}(i)) \tag{25}$$

And the optimal capital utilisation rate:

$$Rrental_t = a'(Z_t) \tag{26}$$

The profit function for entrepreneurs is:

$$P_t(i) Y_t(i) - W_t L_t(i) - Rrental_t K_t^s(i) \tag{27}$$

Then we generate a labor demand equation related to the capital:

$$K_t^s = \frac{\alpha}{1-\alpha} \frac{W_t}{Rrental_t} L_t(i) \tag{28}$$

The marginal cost can be derived as:

$$MC_t = \frac{Rrental_t^{\alpha}(W_t)^{1-\alpha}}{\varepsilon_t^{\alpha}\alpha^{\alpha}(1-\alpha)^{1-\alpha}} \tag{29}$$

According to the Calvo (1983) contract, a certain proportion (ξ_p^s) of entrepreneurs are able to adjust their prices in each period. The objective of the entrepreneurs is to maximize their profits while taking into account the constraints imposed by the demand for intermediate goods. In other words, the problem involves finding the optimal price setting that maximizes profits while ensuring that intermediate goods are demanded in accordance with market conditions.

$$\max_{P_t(i)} E_t \sum_{s=0}^{\infty} \beta^s \xi_p^s \frac{\Xi_{t+s} P_t}{\Xi_t P_{t+s}} Y_{t+s}(i) \left[\widetilde{P_t(i)}(\Pi_{t,t+s}) - MC_{t+s}\right] \tag{30}$$

subject to the intermediate goods demand function:

$$Y_t(i) = \left(\frac{P_t(i)}{P_t}\right)^{-\frac{1+\lambda_{p,t}}{\lambda_{p,t}}} Y_t \tag{31}$$

where ξ measures the fraction of intermediate good producers that will adjust their price level. $\frac{\Xi_{t+s} P_t \beta^s}{\Xi_t P_{t+s}}$ is the firm's nominal discount factor.[2] $\Pi_{t,t+s} = \Pi_{k=1}^{s} \left(\frac{\pi_{t+k-1}}{\pi^*}\right)^{l_p}$. $\widetilde{P_t(i)}$ is the chosen optimal price level.

The optimal price level chosen by intermediate goods producers is:

$$\widetilde{P_t(i)} = \frac{\sum_{s=0}^{\infty} \beta^s \xi_p^s \frac{\Xi_{t+s} P_t}{\Xi_t P_{t+s}} Y_{t+s} MC_{t+s} P_t(i)^{-\omega-1} P_t^{\omega}}{\sum_{s=0}^{\infty} \beta^s \xi_p^s \frac{\Xi_{t+s} P_t}{\Xi_t P_{t+s}} Y_{t+s} P_t(i)^{-\omega} P_t^{\omega}} \frac{\omega}{(\omega-1)} \tag{32}$$

Given that each firm updates its prices using the same mechanism, the aggregate price index for the intermediate goods in the imperfectly competitive market can be derived as follows:

$$P_t = \left[\xi_p \left(P(i)_{t-1}\left(\frac{\pi_{t-1}}{\pi_t}\right)^{l_p}\right)^{\frac{1}{\lambda_{p,t}}} + (1-\xi_p)\left(\widetilde{P_t(i)}\right)^{\frac{1}{\lambda_{p,t}}}\right]^{\lambda_{p,t}} \tag{33}$$

3.6 Capital Producer

In this subsection, we will discuss the behavior of capital producers. Refer to SW07, and capital producer takes prices as given in a competitive market. Each period, they purchase the capital left from the last period with intermediate goods producer, then combine with the newly invested resources. With every unit of investment, they will produce $\left[1 - S\left(\frac{I_t}{I_{t-1}}\right)\right] I_t$ capital. Then the capital evolution equation is:

$$K_t = (1-\delta)K_{t-1} + \varepsilon_t^i \left[1 - F\left(\frac{I_t}{I_{t-1}}\right)\right] I_t \tag{34}$$

[2] According to Smets and Wouters (2007), the nominal discount factor here is equal to the discount factor for the households.

Capital producers are subject to quadratic investment adjustment costs which is specified as $F\left(\frac{I_t}{I_{t-1}}\right)$, with steady state $= 0$, $F' = 0$, and $F''(\cdot) > 0$, I_t is investment, and δ is depreciated rate of capital. ε_t^i denotes the random investment shock following AR(1) progress, specified as: $\ln \varepsilon_t^i = \rho_i \varepsilon_{t-1}^i + \eta_t^i, \eta_t^i \sim N(0, \sigma_i)$. The objective function is the profit function of capital producer:

$$\max E_t \sum_{t=0}^{\infty} \beta^t [P_t^k K_t - P_t^k (1-\delta) K_{t-1} - I_t] \tag{35}$$

Then through the first order condition with respect to I_t, we generate the investment Euler equation:

$$1 = \varepsilon_t^i P_t^k (1 - F(\frac{I_t}{I_{t-1}}) - F'\left(\frac{I_t}{I_{t-1}} \frac{I_t}{I_{t-1}}\right) - \beta E_t \left[\frac{\lambda_{t+1}}{\lambda_t} Pt + 1^k \varepsilon_{t+1}^i F'\left(\frac{I_t}{I_{t-1}}\right)\left(\frac{I_t}{I_{t-1}}\right)^2\right] \tag{36}$$

3.7 External Finance Premium

Due to the existence of asymmetric information between borrowers and lenders, there is a cost associated with the external finance premium charged by banks for credit, which affects the costs of intermediate goods producers, the group of entrepreneurs borrowing to buy capital in excess of their net worth. Specifically, there exists an equation for the external finance premium that is charged to these intermediate goods producers. In each period, they purchase capital K_t from a capital producer at a price P_t^k. In the subsequent period, they can resell the undepreciated capital $(1-\delta)$ back to the capital producer at a price P_{t+1}^k. Similar to the assumptions outlined in Bernanke, Gertler, and Gilchrist (1999), $P(i)_t$ represents the relative price of intermediate goods, while $\frac{\alpha Y t+1}{K_{t+1}}$ is the marginal product of capital, which implicits rental rate of capital. Under these conditions, the expected rate of return of capital for the entrepreneur can be expressed as:

$$E_t \left[R_{t+1}^k\right] = E_t \left[\frac{Rrental_{t+1} + P_{t+1}^k (1-\delta)}{P_t^k}\right] \tag{37}$$

$E_t R_{t+1}^k$ is the expected return on capital. In BGG (1999), it is marked up from the real interest rate by the external finance premium, whose presence is due to an existence of asymmetric information between the lenders and borrowers, i.e., in the case of borrowers' bankruptcy, lenders have to put up some costly monitoring process to recover the capital. Therefore, they demand a higher interest rate than the real risk-free interest rate at which they themselves can obtain their funds. The external finance premium is negatively related to the leverage ratio; that is, increases in borrower net worth reduce agency frictions and lower the external finance premium, stimulating investment and aggregate demand. This dynamic in the model is described by the "financial accelerator" mechanism and the premium pm_t is represented in log-linearised form:

$$E_t r^k_{t+1} - (r_t - E_t\pi_{t+1}) = pm_t = \chi(pk_t + k_t - n_t) + epr_t \quad (38)$$

where $\chi > 0$ measures the degree of the premium response to the leverage. The external finance premium also depends on an exogenous premium shock, epr_t.

To allow for a role of money supply in this mechanism, following Le et al. (2016), we assume that money is the cheapest collateral and can be used to reduce the external finance premium (detailed explanation is in Appendix A). Specifically, we assume that lenders require all firms to put up a fraction of their net worth as collateral before making loans, but the liquidity of collateral would cost a fraction of the collateral's original value. Thus, money can act as the cheapest collateral to eliminate any liquidity cost and thus lower the premium.

Table 1 Balance sheets of each sector in the economy

Firm		Bank		Household		Central bank	
Asset	Liability	Asset	Liability	Asset	Liability	Asset	Liability
$\text{Coll}_{\text{NonM}}(-)$ $\text{Coll}_{\text{M}}(+)$ K(+)	Net worth Credit(+)	Credit(+) M0(+)	Deposit(+)	Deposit(+) GB(−) $\text{Coll}_{\text{NonM}}(+)$	Savings(+)	Borrowing	GB(−) M0(+)

Note: Resources from Le et al. (2014), $\text{Coll}_{\text{NonM}}$ is the collateral in non-monetary form; Coll_{M} is the collateral in monetary form; GB is the government bonds. + and - are used to describe how the balances change with the quantitative easing.

We assume that during crises, the central bank issues M0 in exchange for domestic bonds held by households; households receive M0 and deposit it with banks. Firms use their net worth to acquire as much of this M0 from banks for their collateral purposes, and thus the newly created M0 finds its way to firms' balance sheets as the most liquid collateral pledged to banks in future events of bankruptcy (see Table 1). By varying the M0 supply, the central bank can intervene in the credit market. With M0 acting as the cheapest collateral, the premium is reduced for a given leverage in log-linearised form with an additional term in m^0 (=lnM0):

$$E_t r^k_{t+1} - (r_t - E_t\pi_{t+1}) = pm_t = \chi(pk_t + k_t - n_t) - \psi m^0_t + epr_t \quad (39)$$

Firms' net worth at the end of period t is given by:

$$n_t = \theta n_{t-1} + \frac{K}{N} r^k_t - (\frac{K}{N} - 1)E_{t-1} r^k_t + \varepsilon^n_t \quad (40)$$

where θ is the survival rate of firms, and $\frac{K}{N}$ is the steady-state ratio of capital to net worth. The firms' net worth is given by the past net worth of the θ fraction of surviving firms plus the leveraged realized return on capital, minus the required payment to the banks.

3.8 Monetary Policy

monetary policy in the model operates in two economic states: a normal state where interest rates are adjusted according to the Taylor rule, and a crisis state where the

ZLB limits traditional monetary policy and necessitates the use of QE. During normal times, the central bank sets the nominal interest rate r_t according to the Taylor rule:

$$r_t = \rho r_{t-1} + (1-\rho)(r_p \pi_t + r_y y_t) + r_{\delta y}(y_t - y_{t-1}) + er_t \tag{41}$$

where r_p, r_y, and $r_{\delta y}$ govern the response to inflation and output deviations, ρ denotes interest rate smoothing, and er_t is an exogenous monetary policy shock. M0 was supplied via the discount window to support the broad supply of money M. The equation for M0 during this period is:

$$m_t^0 = \psi_0 + \psi_1 M_t + \text{errm2}_t \quad \text{for} \quad r_t > 0.0625\% \tag{42}$$

where ψ_1 is positive. An additional equation for the supply of money, defined as equal to deposits (credit) + M0, is derived from firms' balance sheets and can be written in log-linearized form as:

$$M_t = (1 + \nu - c - \mu)K_t + \mu m_t^0 - \nu n_t \tag{43}$$

where M, K, m^0, n are the logs of money, capital, M0, and net worth, respectively. Constants are omitted, and ν, μ, c are the ratios of net worth, M0, and collateral to money.

During crises when the nominal interest rate hits or falls below the ZLB, traditional interest rate policies become ineffective. In response, the central bank implements QE, injecting M0 into the economy to stabilize the credit market, M0 targeted the risk premium around its steady state pm^*, aiming to normalize credit conditions. The equation for M0 during this period is:

$$\Delta m_t^0 = \psi_2(pm_t - pm^*) + \text{errm2}_t \quad \text{for} \quad r_t \leq 0.0625\% \tag{44}$$

where ψ_2 is positive.

In the premium equation (Eq.38), the premium is inversely correlated with the broad money supply, indicating a policy of money targeting. This mechanism illustrates how QE policies respond to financial crises by influencing the credit environment until interest rates return above the ZLB threshold, signaling a return to normal monetary policy conditions.

3.9 Fiscal Policy

Fiscal policy in the model closely follows that in SW(07). The government budget constraint is of the form:

$$P_t G_t + B_{t-1} = T_t + \frac{B_t}{R_t} \tag{45}$$

Government spending G_t is set exogenously as a time-varying fraction relative to the steady-state output path, denoted as: $\varepsilon_t^g = \frac{G_t}{Y_t \gamma^t}$ where $\varepsilon_t^g = \rho_g \varepsilon_{t-1}^g + \eta_t^g + \gamma_{ga} \eta_t^a$, following an AR(1) process.

3.10 Market Clearing Condition

The overall resource constraint on the whole economy can be integrated by combining domestic budget constraints and the trade with the Rest of the World (RoW), the economy-wide resource constraint becomes:

$$Y_t = C_t + I_t + G_t + a(Z_t)K_{t-1} + C_t^e + EX_t - IM_t \tag{46}$$

where C_t^e is entrepreneurs' consumption, which equals net worth, as firms that die in period t will consume their net worth and depart from the scene.

The full model is listed in Appendix B.

4 Indirect Inference

We use the method of Indirect Inference, which was first proposed by Smith (1990) and then extended by Gourieroux et al. (1993), Gourieroux and Monfort (1995) and Canova (2007). Indirect inference uses an auxiliary model as a descriptor of the data, which is entirely independent of the theoretical model. The target of the method is to find a set of parameters which makes the behaviour of the auxiliary model from simulated data closest to the one based on the actual data; this amounts to minimising the model Wald statistic which reflects the probability of the data-based auxiliary model. The indirect inference method applied in this work is that proposed by Meenagh et al. (2009) and refined by Le et al. (2012) with Monte Carlo experiments. They compared the power of the indirect inference test with that from Maximum Likelihood and found that the power of indirect inference is much higher in small samples.

4.1 Indirect Inference estimation

The model has two sets of parameters: steady-state values, such as the investment-output ratio and the capital-output ratio, which are fixed based on observable data; and parameters related to agents' behavior, which are estimated. We use a random search with jumps to find the optimal values of the latter group of parameters. This method starts from an initial point and explores the parameter space by considering neighboring states and choosing to move the system to other states or stay in the current state. This approach has proven robust and independent of the initial values, as we obtained the same estimates through this procedure.

In this paper, we employ unfiltered non-stationary quarterly data spanning from 1985Q1 to 2016Q4. Due to the non-stationarity of the data, we use a VECM as the auxiliary model descriptor of data. In practice this is a VARX(1) [3] with a deterministic trend and the non-stationary productivity residual as an exogenous variable, which equates to a cointegrating relationship.

Table 2 shows the estimation results, which indicate that the Wald statistic of 41.67 for a VAR model of the three central variables, output, interest rate, and inflation (y, r, π), is not rejected, with the maximum p-value at 0.253 (¿0.05). This result

[3] We used the ADF and KPSS tests to check shock stationarity. All shocks, except for productivity, were stationary or trend stationary. As productivity shock was integrated of order one, we modeled it as an ARMR(1,1,0) after differencing.

Table 2 Structural Parameter Estimates and test results

Description	**Symbols**	**Calibration**	**Estimation**
Household sector			
Discount factor	β	0.99	0.99
Elasticity of consumption	σ_c	1.39	1.26
Elasticity of labor supply	σ_l	2.83	2.70
External habit formation	h	0.70	0.79
Degree of wage stickiness	ξ_w	0.70	0.83
Degree of Wage indexation	l_w	0.58	0.68
Proportion of sticky wage	w^w	0.10	0.08
Preference bias in consumption	ω	0.70	0.70
Firm sector			
Degree of price stickness	ξ_p	0.67	0.85
Degree of price indexation	l_p	0.43	0.26
Proportion of sticky price	w^p	0.40	0.38
Entrepreneur Survival rate	θ	0.99	0.99
Capital share in production	α	0.30	0.15
Capital depreciation rate	δ	0.05	0.05
Fixed cost in production	ϕ	1.50	1.54
Elasticity of capital adjustment	φ	5.74	8.02
Elasticity of capital utilisation	ψ	0.05	0.13
Monetary policy			
Talyor rule response to inflation	r_p	2.30	2.55
Interest rate smoothing	ρ	0.74	0.63
Talyor rule response to output	r_y	0.03	0.02
Talyor rule response to output change	$r_{\delta y}$	0.20	0.20
M0 response to M2	ψ_1	0.05	0.01
Money response to credit growth	ψ_2	0.04	0.13
Financial friction			
Elasticity of premium to leverage	χ	0.04	0.06
Elasticity of premium to money	ψ	0.08	0.06
Test results			
Wald value			41.674
P-value			0.253

suggests that the model passes the Wald test with ease. In addition, Table 4 demonstrates that the individual VARX (1) parameters are within the 95% bounds based on simulated data, indicating a good fit of the model to the data.

Table 3 Statistical properties of shock

Description	**Symbols**	**AR(1) coef**
Government spending shock	ρ_g	0.8034
Preference shock	ρ_c	0.4526
Investment shock	ρ_I	0.5198
Taylor rule shock	ρ_r	0.1877
Productivity shock	ρ_a	0.6521
Price mark-up shock	ρ_p	0.6008
NK wage mark-up shock	ρ_{wnk}	0.4533
NC wage mark-up shock	ρ_{wnc}	0.7689
Risk premium shock	ρ_{pm}	0.2390
Net worth shock	ρ_n	0.3453
Quantitative easing shock	ρ_{m0}	0.0912
Export demand shock	ρ_{ex}	1.2476
Import demand shock	ρ_{im}	1.9351
Foreign interest rate shock	ρ_{rf}	0.4786
Foreign consumption shock	ρ_{cf}	0.6139

Table 4 VECM parameters and Bootstrap Bounds for y π r with estimated parameter

$y\pi r$	Actual VAR Coefs	Lower Bound	Upper Bound	In/Out
b_{yy}	0.9463	0.1568	1.3762	In
$b_{y\pi}$	-0.0231	-1.3833	2.320	In
b_{yr}	-0.3387	-1.219	1.087	In
$b_{\pi\pi}$	0.3129	0.1335	0.4382	In
$b_{\pi y}$	0.0712	-0.2248	0.2850	In
$b_{\pi r}$	0.029	-0.008	0.1733	In
b_{rr}	0.8810	0.4195	0.9332	In
b_{ry}	0.0427	-0.011	0.1782	In
$b_{r\pi}$	0.0210	-1.763	0.5482	In

4.2 Robustness check

In order to assess the robustness of our estimation procedure, we conducted a Monte Carlo experiment. We assumed that the estimated model was the true model and then created a false model by altering the estimated parameters by a certain percentage. Specifically, we increased or decreased the estimated parameters by +x% or -x% and then tested whether the resulting model was still consistent with the data.

Table 5 shows the rejection rate for different levels of parameter falseness, ranging from 1% to 10%. The rejection rate increases sharply with increasing falseness, indicating that our test has strong power. For example, when we falsified the model by 10%, the model was 100% rejected, meaning that our estimated coefficients cannot deviate from the true coefficients by more than 10% for the model to be valid.

Table 5 Monte Carlo Power test

Parameter Falseness	True	1%	5%	7%	10%
Rejection rate	5%	12.1%	55.86%	78.4 %	100 %

4.3 The Variance decomposition of shocks

Table 6 provides insights into the various factors that impact key variables' variation. Productivity is the dominant contributor to output variation, accounting for over a third of the variation. Among financial shocks, the external finance premium explains approximately 10% of the variation. Export and import demand shocks, as foreign shocks, each contribute around 5% to the variation. Monetary policy exerts a total impact of 10%, which is evenly split between the Taylor rule and QE shocks. The influence of other shocks on output variation is relatively minor. The patterns of consumption variation are similar to those of output variation.

Regarding financial variables, interest rate movements are mainly driven by shocks to productivity, monetary policy, and the bank premium. These same shocks are the primary drivers of exchange rate variation as well. Additionally, trade shocks significantly impact exchange rates.

Table 6 Variance decomposition of shocks : 2006Q1 to 2016Q4

Shocks	Exchange rate	Output	Consumption	Interest rate
government spending shock	3.432334	5.008639	1.3332652	2.1071515
preferences shock	1.042222	1.108837	12.910514	0.0016258
Investment shock	3.809868	8.071381	2.0001068	4.0051501
Monetary policy shock	4.67901	5.812723	4.9710416	35.217756
Productivity shock	32.98789	36.37000	22.009242	19.161725
Price mark-up shock	4.876478	10.862621	9.547019	5.5119655
Wage mark up	1.46E-05	0.000024	2.763E-05	4.439E-07
Labour supply	4.013433	5.033975	2.0003234	0.0061056
Premium shock	6.876755	9.674527	22.0093845	15.003631
Networth shock	3.798575	1.085220	10.000833	3.0006949
Quantitative easing shock	0.876487	5.000011	4.3610951	9.6402881
Export shock	14.89716	6.000595	4.4369885	4.1979336
Import shock	18.70903	5.000301	4.4197725	2.1404486
Total	100	100	100	100

4.4 Dynamic response from the model

Taylor rule shock

Figure 1 depicts the IRFs to a positive Taylor rule shock, which increases the nominal interest rate of the baseline model. Notably, when the economy gets into the ZLB crisis, the Taylor rule will be suspended, so the monetary policy shock only applies to the model without a ZLB crisis. A standard Taylor rule transmission mechanism suggests that a monetary policy contraction usually discourages borrowing, investment, and consumption and reduces output. Then the downward pressures on the demand side are gradually fed through the changes in the output. Meanwhile, the output gap can lead to a lower inflation level. The demand for labor also falls with reduced aggregate demand in the labor market. In terms of the financial sector, the falls in the capital price lower the net worth of the entrepreneur. Consequently, the external finance premium is pushed up, then works counter-cyclically with an amplified impact that further reduces lending and investment.

In the foreign sector, deflation and a higher nominal interest rate appreciate the British pound with a higher real interest rate, which also reduces the real exchange rate, then makes exports less competitive with a higher demand for imports. The net foreign bond position decreases overall and gets back after around ten quarters.

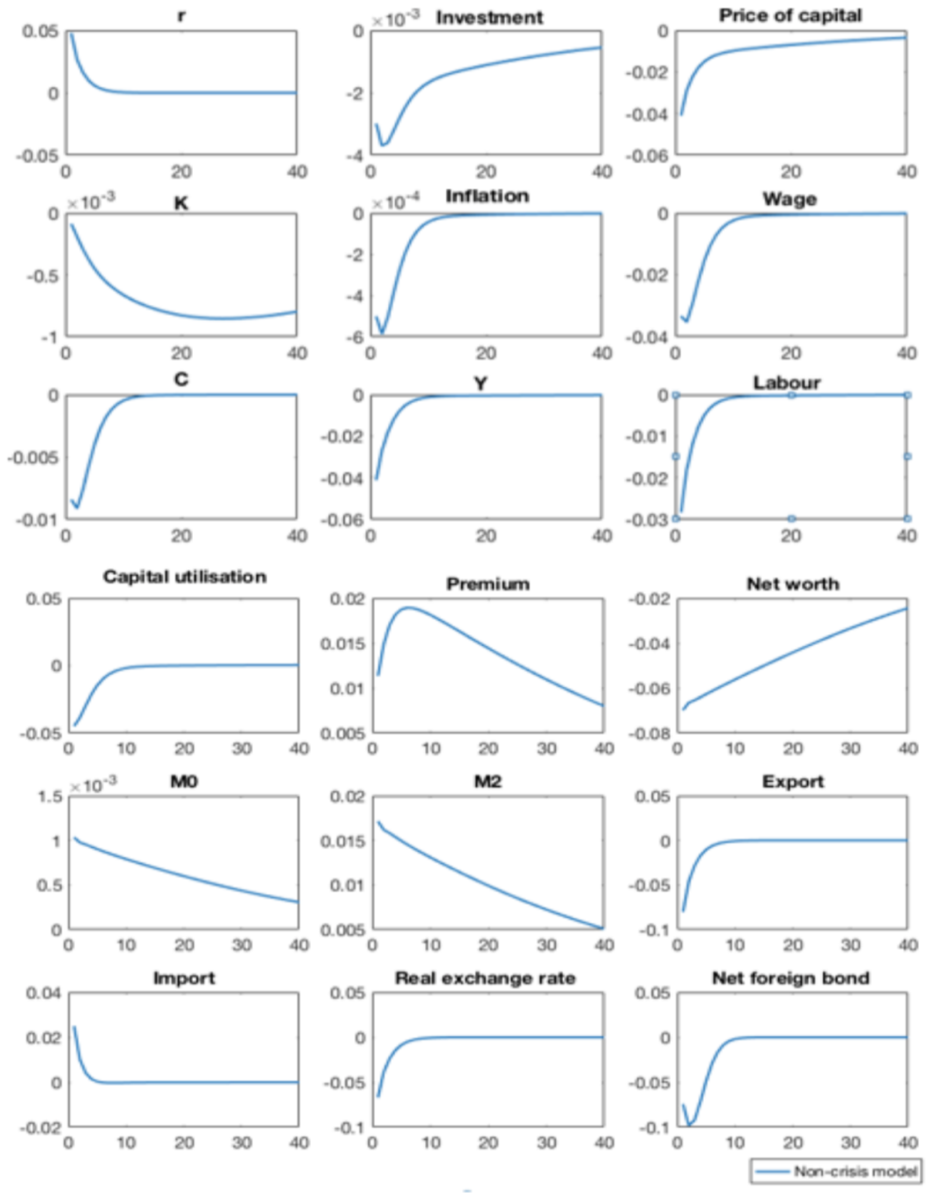

Fig. 1 IRFs to a monetary policy shock: Note that the time intervals on the x-axis are in quarters. The units on the y-axis represent percentage deviations, except for the interest rate, inflation, credit spread, real lending rate, and net foreign assets, which are reported as percentage-point deviations.

Quantitative easing shock

Figure 2 depicts the response to a QE shock in two different models. According to the previous chapter, the model is composed of two states. In the initial state, called the "normal state," active rate policy management is enabled, as indicated by the blue solid line. As a result of the ZLB becoming binding, the red dotted line represents the state of a crisis scenario, requiring QE to be implemented. These impulse responses provide valuable insights into the impact of QE on a ZLB-constrained economy. Our analysis reveals that QE, which involves injecting money through significant asset purchases, mitigates default risk and external finance premiums, resulting in a positive impact on demand-side variables. We find that, compared to the model without ZLB constraints, consumption responses are stronger, and inflation is bolstered, leading to a rapid reduction in the real interest rate. The lower real interest rate subsequently triggers a depreciation of the British Pound in the foreign sector, leading to a more competitive export market. Additionally, we observe that import responses are higher compared to the baseline environment. This is because the traditional monetary policy rule does not have a contractionary effect on the increased money supply.

Our results suggest that monetary policy encompasses more than just adjusting policy rates. These findings are consistent with previous studies, such as Le et al. (2016), which conclude that QE can play a pivotal role in reviving an economy during a recession, including the ZLB crisis.

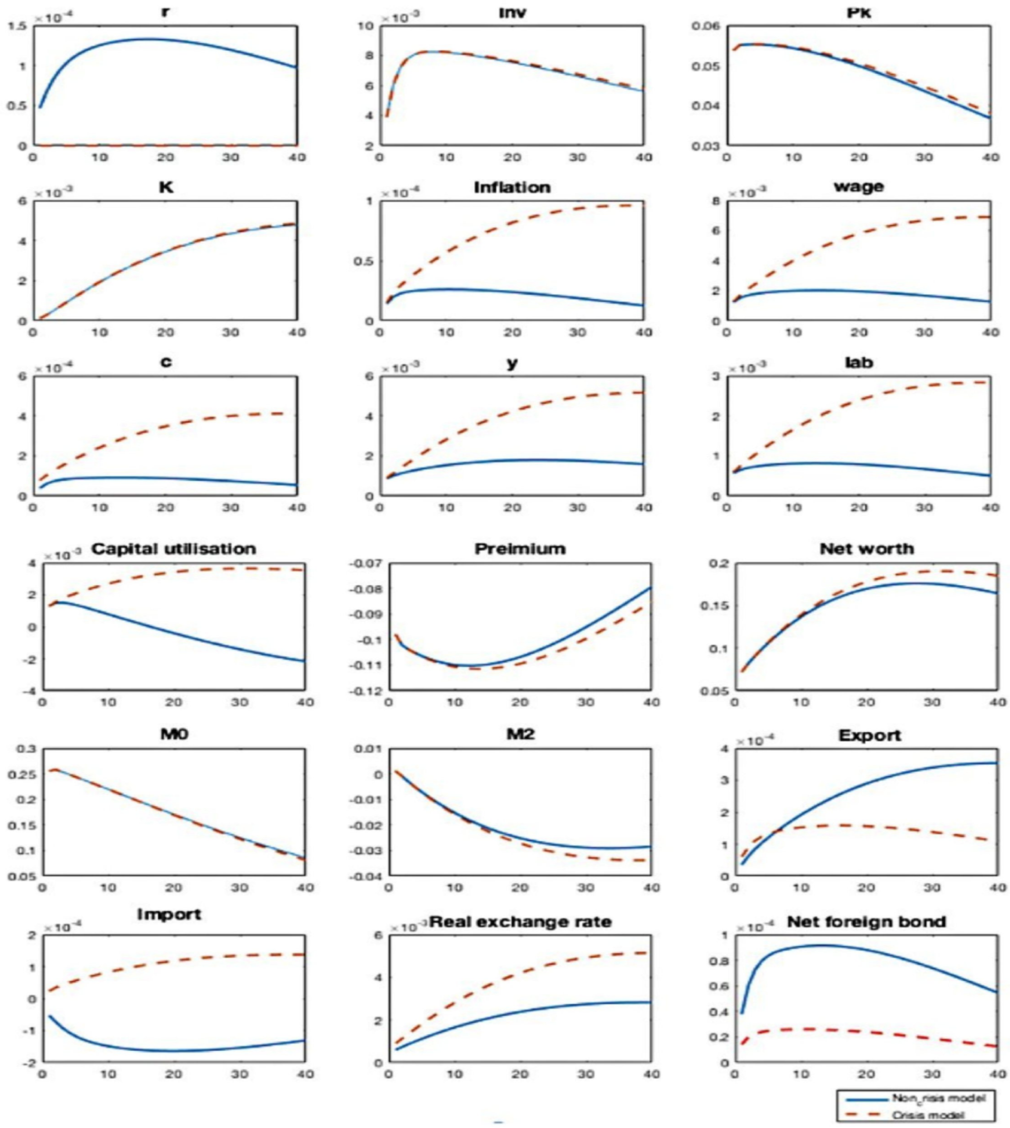

Fig. 2 IRFs to a QE shock in Both Non-Crisis and Crisis Models: Note that the time intervals on the x-axis are in quarters. The units on the y-axis represent percentage deviations, except for the interest rate, inflation, credit spread, real lending rate, and net foreign assets, which are reported as percentage-point deviations. The blue solid line represents the responses under the normal state, while the red dash-dotted line represents the responses under the crisis state.

Fiscal policy shock Figure 3 illustrates the impact of an expansionary fiscal policy, which is captured through a fiscal multiplier. Our results show that higher government spending leads to higher aggregate demand, pushing up inflation and the price level. The nominal interest rate also rises via the response of the Taylor rule. The increase in government spending also leads to a direct increase in output, which in turn induces higher expectations for income among consumers, resulting in higher consumption. In the labour market, firms provide higher wages to attract labour, leading to an increase in both investment and capital price for the accelerated production process. The higher value of capital indicates that the net worth on entrepreneur balance also increases, resulting in a lower external finance premium required by the bank. Additionally, the counter-cyclical effect of premium further increases the net worth of the entrepreneur, leading to more lending and investment.

In the foreign sector, the increase in domestic demand leads to an increase in imports to satisfy this demand, which could result in an appreciation of the real exchange rate (a decrease in Q) and an appreciation of the British pound. However, this weakens the competitiveness of domestic goods in the foreign market, leading to a drop in export, and consequently, a decrease in the accumulated net foreign asset.

When the model is constrained by the ZLB, we observe a slightly higher response from the demand side, including consumption, capital, and investment, due to a lack of contraction from the monetary policy, which could give downward pressure on the demand side. In the foreign sector, there is a devaluation of the domestic currency due to a lower real interest rate, making exports more competitive. Import is also slightly increased to satisfy excess domestic demands. Finally, we observe an increase in the accumulated net foreign asset.

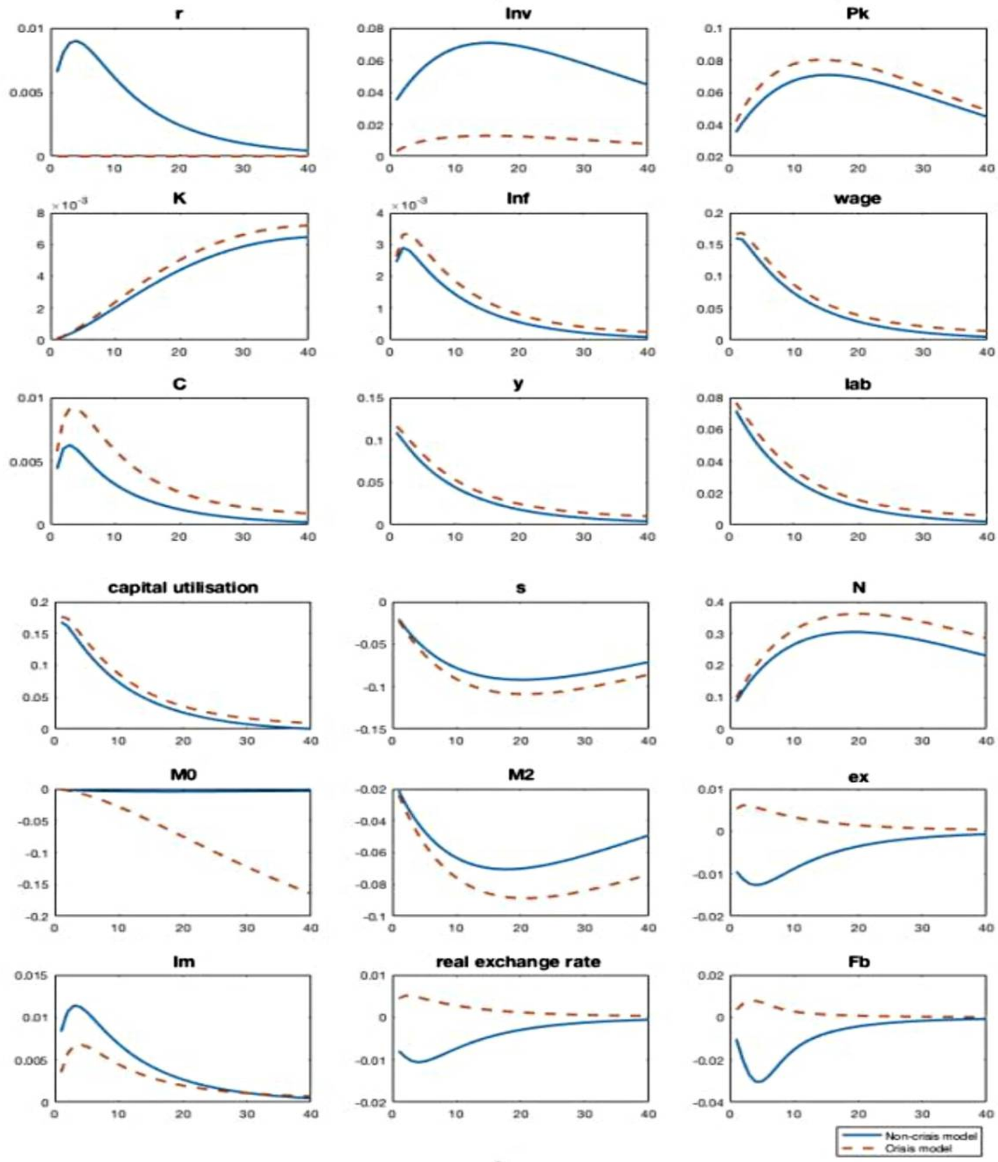

Fig. 3 IRFs to a Government spending shock in Both Non-Crisis and Crisis Models: Note that the time intervals on the x-axis are in quarters. The units on the y-axis represent percentage deviations, except for the interest rate, inflation, credit spread, real lending rate, and net foreign assets, which are reported as percentage-point deviations. The blue solid line represents the responses under the normal state, while the red dash-dotted line represents the responses under the crisis state.

4.5 Causes of the crisis

Using our sample analysis, we explore further what a crisis is, what causes it, and what it means. A crisis is defined as an interruption of output for at least three years, while a financial crisis constitutes a crisis with a binding ZLB on nominal interest rates. In practice, we bootstrap the shocks based on UK observations from 1985Q1 to 2007Q4 to develop a sample of "standard shock scenarios", during which there are no major financial shocks. In parallel, shock samples for 1985Q1 through 2016Q4 are gathered as "crisis-inclusive scenarios".

We simulate the model with two sets of shocks and compare their effects. Based on the bootstrap simulation examples in Figures 6 and 7, the following results were found. Shocks without financial shocks cause real crises but not financial crises. Crisis is a normal part of the UK economy. Under the "standard shock scenarios," without financial shocks, there are several significant drops in output while the ZLB was not hit, as shown in Figure 4. Figure 5 shows that financial crises and major recessions are more likely when financial shocks are included. The Great Recession was thus a crisis and a financial crisis triggered by both real and financial shocks. Financial shocks alone are not sufficient to create a significant economic crisis. In our bootstrap scenarios using only financial shocks, there was no economic crisis.

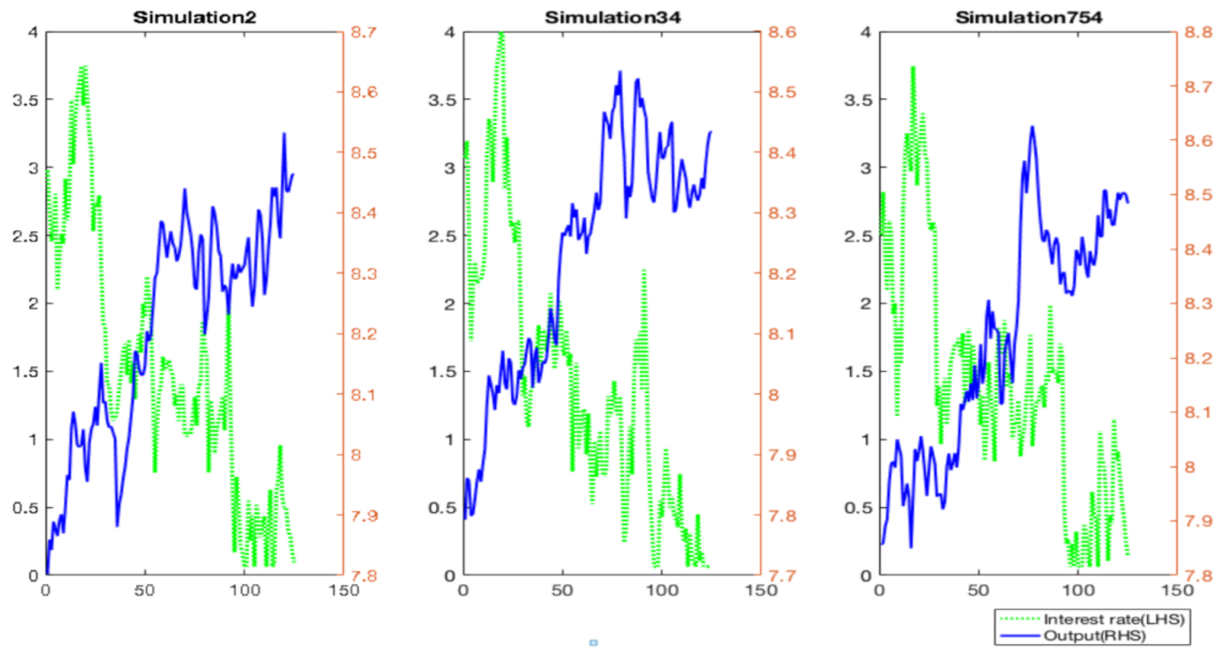

Fig. 4 Crises without financial crisis

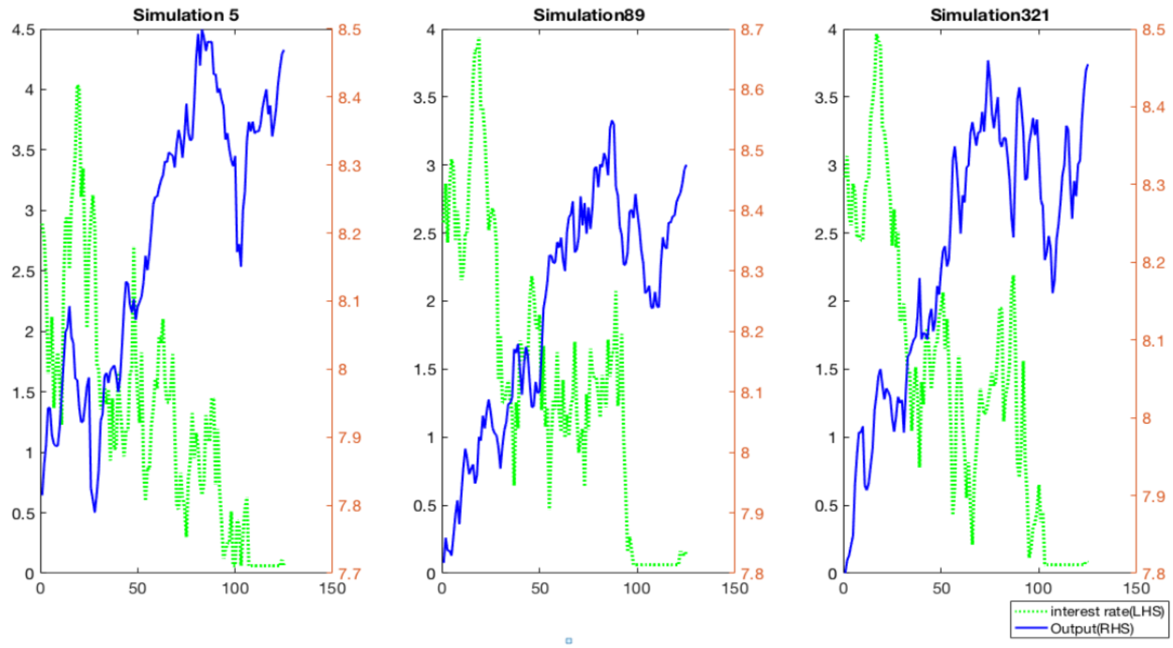

Fig. 5 Crises with financial crisis

5 Policy Implications

The choice of an optimal monetary target has been a longstanding issue in monetary economics, but empirical evidence on the matter is scarce[4]. Two alternatives that have received significant attention are price-level targeting (PLT) and nominal GDP targeting (NGDPT). In the next section, we explore the implications of the UK model that we have estimated for the potential effects of transitioning to PLT or NGDPT as a monetary rule.

5.1 Inflation targeting implications of the model

Inflation targeting is a traditional monetary policy where the central bank sets a specific inflation rate as its target and stabilizes the economy by keeping inflation anchored to its long-run target. It was introduced in the 1990s to help reduce inflation expectations and avoid high inflation. Inflation targeting has been widely employed by developed countries, such as the US, UK, and EU countries, since then. It is the monetary rule estimated in our model as:

$$r_t = \rho r_{t-1} + (1-\rho)(r_p \pi_t + r_y y_t) + r_{\delta y}(y_t - y_{t-1}) + er_t \tag{4.1}$$

[4]Sweden experimented with price-level targeting in the 1930s for a brief period of around two years, but this did not yield much insight due to the short duration of adoption. For more details, see Jonung (1979) and Berg and Jonung (1999)

where ρ measures the interest rate smoothing, and $(1 - \rho)$ captures the short-run feedback from inflation and output gap.

The global crisis in 2008 exposed critical flaws in inflation targeting and fuelled recent interest in optimal monetary policy. In the aftermath of the financial crisis, when interest rates hit the ZLB, so reducing monetary policy potency, some researchers have proposed setting a higher inflation target under inflation-targeted rules in an attempt to solve the ZLB crisis- for example, Krugman (1998), Woodford and Eggertsson (2003), and Bernanke (2017). Alternatively, Hatcher and Minford (2014) suggest that price-level targeting could be a valuable mechanism for helping the economy recover from deflationary shocks.

To compare the ability of each monetary regime to stabilise the economy and avoid financial crisis, we perform bootstrap simulations with a large sample size to measure the frequency of crises and welfare costs of different regimes. As shown in subsection 4.3, under the baseline inflation targeting regime, there would be 99.9 crises per 1000 years, and the welfare cost for" Output "and" Inflation "are 2.84 and 0.025, respectively.

5.2 Alternative monetary policy

Price-level targeting

Price-level targeting (PLT) is a monetary policy strategy in which the central bank sets a specific path for the price level and commits to correcting deviations from that path within a given period. Unlike inflation targeting, which aims to stabilize inflation, PLT provides more guidance to the economy. As noted by Sbensson (1999), using PLT can help solve the time-inconsistency problem. With rational expectations, PLT can lead to lower inflation and output variability, essentially providing a free lunch.

PLT has two key advantages over inflation targeting:

First, under inflation targeting, past deviations from the target are effectively ignored, whereas PLT takes history into account and corrects past deviations. This approach affects the expectations of the forward-looking public, making PLT a more effective tool for maintaining price stability. For instance, if inflation unexpectedly rises from 2% to 3%, inflation targeting would simply allow the deviation to continue, gradually approaching the target. In contrast, PLT would require a below-average inflation rate and maintain a specific price-level path, promoting stability over time. Although PLT may result in longer reactions to inflation deviations, it ensures price and inflation stability in the long run, making it a valuable monetary policy tool.

Secondly, when the nominal interest rate is constrained by the zero lower bound, an unexpected change in aggregate demand can cause real interest rate to rise under an inflation targeting scheme. This can result in a decrease in inflation expectations and an increase in recession risk. However, under price-level targeting with an inflation target of 2%, people expect inflation to exceed 2% since past deviations are not ignored, and the central bank can make up for any shortfall. This expectation stimulates aggregate demand and increases the price level. Eggertsson and Woodford (2003) confirmed this intuition, finding that price-level targeting reduces welfare losses during financial and zero-bound crisis periods, as compared to inflation targeting in New Keynesian models. Additionally, Coibion et al. (2012) found that price-level targeting can reduce the frequency and severity of zero-bound episodes. Other studies, such as Coletti and Woodford (1999), Dittmar, Gavin, and Kydland (1999), and Dittmar and Gavin (2000), provide further evidence in support of price-level targeting.

To perform the empirical study, we specify the price-level targeting as follows:

$$r_t = \rho_1 r_{t-1} + (1 - \rho_1)\{\rho_p(p_t - p^*) + \rho_y(y_t - y^*) + \rho_{\delta y}[(y_t - y^*) + (y_{t-1} - y^*)]\} + er_t \quad (4.2)$$

where the steady-state of price level p^* is assumed constant and normalized to 0, practically, we choose the average value of output from actual data as the steady-state value of output as y^*. ρ_1 is the interest rate smoothing rate, and ρ_p is the value of Taylor rule response to price level, and ρ_y and $\rho_{\delta y}$ are Taylor rule response to output and output change respectively. We estimate the parameters in the above equation by minimizing the crisis times. We search for the values which can allow the model to stabilize the economy most by simulation:

$$r_t = 0.545 * r_{t-1} + (1 - 0.545)\{1.745 * (p_t - p^*) + 0.02 * (y_t - y^*) + 0.03 * [(y_t - y_{t-1}]\} + er_t \quad (4.3)$$

From table 8, with a single price-level targeting adopted, there has been a significant decrease in the frequency of economic and financial crises compared with the results generated by inflation targeting. Within the expected 1000 years, the frequency of both crises comes down to 87. The total welfare cost drops from 2.87 to 0.724 with a significant contribution from output variance, which drops down to 0.698.

Nominal GDP targeting

This section will discuss another desirable strategy for monetary policy, nominal GDP targeting or nominal income targeting, which strives to get a certain level of nominal GDP growth. The most attractive feature of the nominal GDP targeting is closely related to output and prices, which are the variables the central bank cares about most. Frankel (2012) concluded that the central bank under nominal GDP makes decisions regarding the importance of inflation and real output rather than the breakdown between the two.

Additionally, superior to inflation targeting, it can respond effectively to demand and supply shock. For example, facing a negative supply shock, there will be a decline in output and a rise in inflation. Under inflation targeting, the central bank would choose to carry out the contractionary monetary policy to maintain a lower inflation rate, but at the cost of further exacerbating the recession. In contrast, nominal GDP targeting can avoid a worse situation by an expansionary monetary policy and return the nominal GDP to target. Though the inflation rate will be temporarily above the potential, it can decrease unemployment by letting inflation rise, particularly during the recession.

The NGDP targeting can avoid default and create more financial stability on the front of financial friction. Koenig (2013) and Sheedy (2014) remarked that if the aggregate income can keep close to the steady growth path by nominal GDP targeting, it would not fall as much during the recession, allowing people to repay their loans, then avoid default and bankruptcy.

Then we bootstrap our model with nominal GDP targeting, and the rule is defined as follows.

$$r_t = \rho_1 r_{t-1} + \rho_y(y_t + p_t - \bar{y} - \bar{p}) + er_t \tag{4.4}$$

where $y_t + p_t - \bar{y} - \bar{p}$ indicates the deviation of the nominal GDP from targeted value. $\bar{p} = 0$ and $\bar{y}$ follow the real output data. ρ_y is treated as the partial elasticity of interest rate responding to the nominal GDP deviation. The parameters that minimized crisis were :

$$r_t = 0.625 * r_{t-1} + 2.21 * (y_t + p_t - 8.71) + er_t \tag{4.5}$$

Nominal GDP targeting has the potential to significantly reduce economic volatility. Table 7 presents the results of simulations, which show that the financial crisis can be reduced from 87 to 66 when compared to the price-level targeting case, indicating that nominal GDP targeting is more effective in lowering zero-bound episodes than the other two rules. In terms of welfare cost, the output variance is the lowest at 0.690, and the inflation variance is similar to that of the inflation-targeting rule at 0.025. Overall, the simulated results suggest that nominal GDP targeting and price-level targeting are more effective than the traditional inflation-targeting rule in stabilizing the economy.

5.3 Combining the monetary rules with the use of QE in the ZLB- "Monetary reform"

We also consider these different regimes in combination with the use of QE when the ZLB is triggered, which we term "monetary reform." Table 7 brings all these results together. It shows that crises are reduced further under either combination than the single rule adopted. NGDPT + Monetary reform outperforms the other two types of monetary regimes in the standard welfare cost measure which is based on the sum of the variances of output and inflation. These variances represent the deviations from their optimal or target levels, which negatively impact the overall utility of households and entrepreneurs in the economy. By integrating these effects into the agents' utility functions, we quantify the welfare costs and observe that the NGDPT + Monetary reform regime achieves the lowest combined welfare cost value of 0.580, indicating superior performance in stabilizing both output and inflation compared to the other monetary regimes.

To further present how different monetary regimes behave in stabilizing the economy, in Figures 6 and 7, we plot the graphs for simulated "output" [5] from randomly drawn examples. It shows that alternative monetary regimes can better stabilize the economy, particularly after combining with monetary reform. It is easy to detect several significant fluctuations with inflation targeting (solid blue line). However, there

[5] By applying identical shocks to both models, any observed differences are solely attributed to the varying monetary policy regimes.

Table 7 Frequency of Crisis under Different Types of Monetary Regimes

	Inflation targeting	Inflation targeting+Monetary reform	Price level targeting	NGDPT	PLT+Monetary reform	NGDPT+Monetary reform
Economic Crisis						
Duration between two crises	10.01	10.84	11.41	10.58	18.11	17.24
Frequency of crisis (expected economic crisis per 1000 years)	99.90	91.91	87.64	94.51	55.21	58.00
Financial Crisis						
Duration between two crises	10.12	10.98	11.42	14.94	19.97	20.04
Frequency of crisis (expected economic crisis per 1000 years)	98.78	91.07	87.62	66.93	50.08	49.90
Welfare analysis						
Var(output)	2.840	1.668	0.698	0.690	0.683	0.552
Var(inflation)	0.025	0.023	0.026	0.025	0.025	0.028
Var(output)+Var(inflation)	2.865	1.691	0.724	0.715	0.708	0.580
Var(consumption)	1.458	0.896	0.910	1.003	0.458	0.567

is more stability created by other regimes. For instance, the big ups and downs under inflation targeting are squashed with alternative regimes at periods 20 to 30. The price-level targeting and nominal GDP targeting can perform better, especially when the crisis collapses. Around the period 90, there was a significant slump under the inflation targeting (solid blue line). While under the PLT+monetary reform (solid red line) and the NGDPT+monetary reform (solid grey line), the big crisis is stabilized into a moderate drop or small swings and lasts for a shorter period.

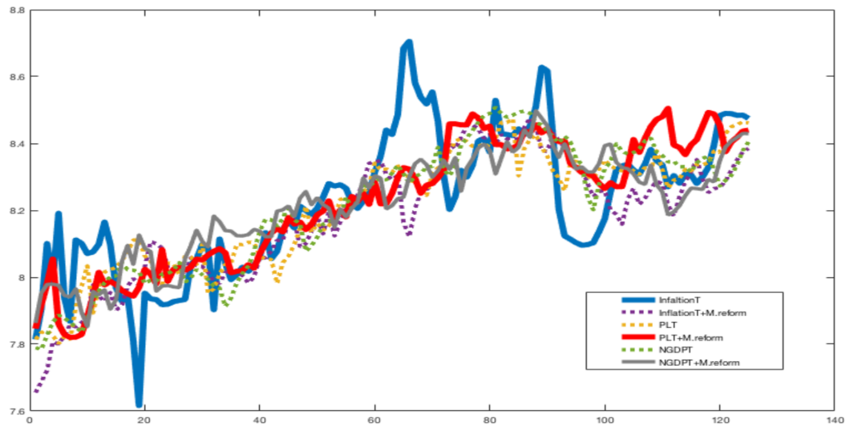

Fig. 6 Simulated output under different rules (Example1)

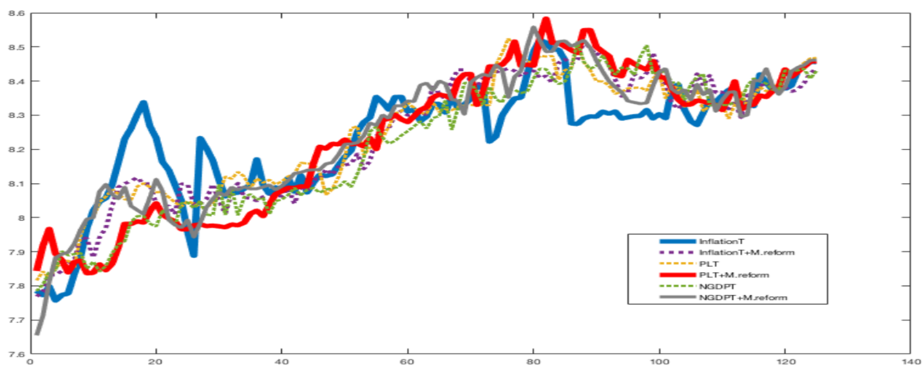

Fig. 7 Simulated output under different rules (Example2)

5.4 The role of fiscal policy

A further important policy issue is the role of fiscal policy in this context where monetary policy is also being optimized and is using unconventional methods, notably QE, at the ZLB. It could well be the case that fiscal policy can reduce the challenges faced by monetary policy, in particular by dealing more effectively with the ZLB, so reducing the pressure to use QE. In this section we investigate this important issue by considering two possible fiscal policies- one in which fiscal policy follows a strong counter-cyclical rule and another in which it reacts rapidly to any threat of reaching the ZLB, by pushing fiscal intervention to whatever is needed to prevent interest rates reaching it. We do this while maintaining monetary policy at their optimized rules as set out above. The following are three different fiscal policy regimes:

1 **Baseline policy regime**

$g_t = \rho_g g_{t-1} + \rho_a e_t^a + e_t^g$

Where g_t is the government expenditure shock ; e_t^a is the productivity i.i.d innovation; e_t^g is the goverment expenditure i.i.d innovation

2 **Suppressing fiscal policy regime**

$g_t = \rho_g g_{t-1} + \rho_a e_t^a + e_t^g + f_t$

where f_t is a fiscal shock pushing interest rate out of the ZLB

3 **Strong fiscal feedback policy regime**

$g_t = \rho_g g_{t-1} + \rho_a e_t^a + e_t^g - \theta(y_t - \bar{y}_t)$

where $\bar{y}_t$ is the base run output , (y_t-$\bar{y}_t$) is the output gap ; $\theta = 1$

Table 8 shows the results of adding these two fiscal rules to the policy mix. What it reveals is that fiscal policy has a major contribution to make in stabilizing the economy, both output and inflation. It can make a substantial inroad into instability by suppressing the ZLB when it threatens to occur. However, it makes an even bigger inroad when it reacts forcefully in a counter-cyclical way at all times; this also largely prevents the emergence of the ZLB, by preventing the violent lurches in output and inflation that trigger the large interest rate changes that hit the ZLB. Simulations of this policy combination imply the ZLB is only hit 3% of the time, effectively sidelining it; meanwhile the fiscal stabiliser greatly lowers output variance while keeping inflation variance low. The welfare measured by sum of variance of output and inflation is minimised in this policy combination, revealing the importance of having a fiscal component in the policy mix. The figure below shows the simulated output paths for a typical simulation under each policy regime. It can be seen clearly how output is stabilized compared with the optimal monetary regime alone.

Table 8 Variance of Simulations

Variance	**Baseline NGDP Targeting**	**ZLB-suppressing Fiscal Shock**	**Strong Fiscal Feedback**
Non-crisis + Crisis Model			
Var(output)	0.0108	0.0067	0.0034
Var(inflation)	0.0371	0.0282	0.0251
Var(output) + Var(inflation)	0.0425	0.0350	0.0284

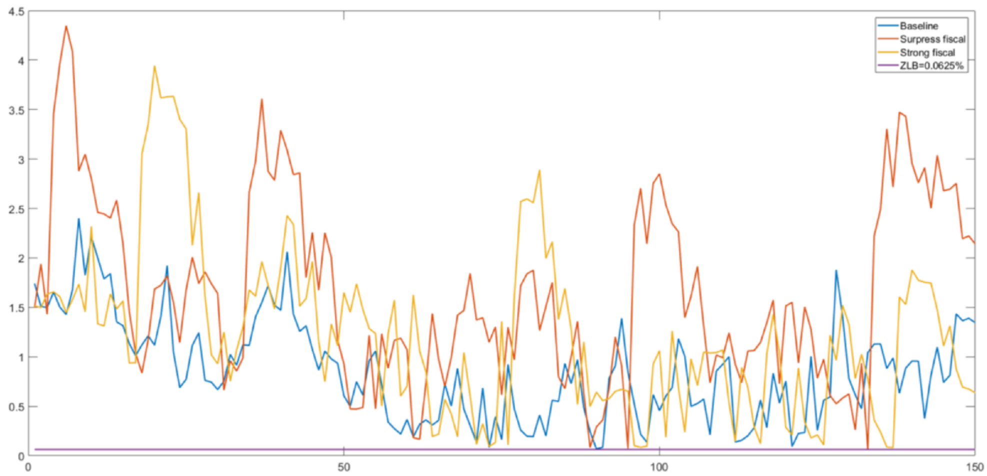

Fig. 8 Example of interest rate simulations under different regimes

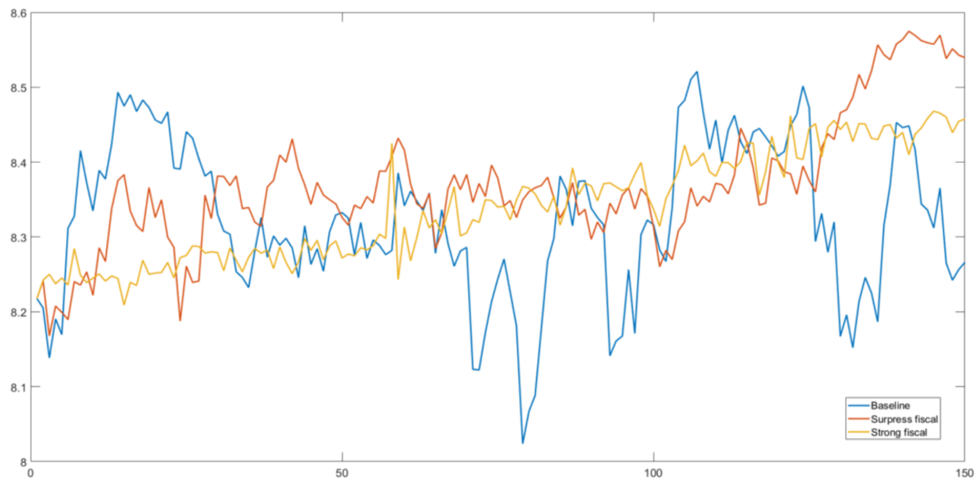

Fig. 9 Example of interest rate simulations under different regimes

6 Conclusion

This work is based on the ongoing challenge for monetary policy during the aftermath of the financial crisis in 2008. When conventional monetary policy was limited by the zero lower bound, the central banks turned to unconventional monetary policy, such as quantitative easing. In light of the impressive developments in monetary policy, we would like to better understand the unconventional monetary tool by studying its transmission mechanism through the financial intermediary, for example.

According to the transmission method proposed by Le et al. (2016), we analyzed quantitative easing through the bank lending channel to capture the dynamic response to unconventional monetary policy. Ultimately, the model shows the importance of unconventional monetary policy, showing that the money supply needs to be controlled to ensure economic stability. Besides, both monetary policy and expansionary fiscal policy have proven beneficial to the economy, including the zero lower bound period. The model's estimation results indicate that it can explain the observations well and replicate the fluctuations of the key endogenous variables: output, inflation, and interest rate, for which we are primarily concerned. Notably, we employed the indirect inference method to investigate whether the model could explain the data behaviour in the UK.

Simulation results show that monetary policy and monetary reform significantly improve monetary regime behavior. In particular, monetary reform can help squash the enormous crisis and stabilize the economy with fewer significant fluctuations from simulated output under various schemes. Based on our study, nominal GDP targeting and monetary reform have the lowest welfare cost and crisis frequency. Thus, we argue that the single Taylor rule will not be enough to combat financial friction. A better-performing monetary regime, such as nominal GDP targeting combined with monetary reform, could be considered.

In terms of fiscal policy, we first examined a ZLB-suppressing fiscal policy that consistently employs fiscal expansion to prevent the rate from falling into the ZLB. Additionally, we proposed a strong active fiscal policy that responds aggressively to the output gap. Our analysis indicates that fiscal policy plays a crucial role in stabilizing the economy by suppressing the ZLB and reacting counter-cyclically, thereby preventing violent fluctuations in output and inflation that may trigger large interest rate changes at the ZLB. While our study has made substantial progress in exploring the challenges faced by monetary and fiscal policies, further exploration of the model is still necessary. We hope that our study's findings will contribute to ongoing efforts to enhance economic stability and inform policymaking.

7 Disclosure of interest

We wish to submit an original research paper "UK monetary and fiscal policy since the Great Recession- an evaluation" for consideration by the journal " Applied Economics".

We confirm that this work is original and has not been published elsewhere, nor is it currently under consideration for publication elsewhere.

This paper explores the economic impacts of the Bank of England's quantitative easing policy, implemented as a response to the global financial crisis. Utilizing an open economy DSGE model, our research contributes to the understanding of monetary policy effectiveness, particularly when nominal interest rates are at the zero lower bound. Through the application of the indirect inference method, we estimate and test the model, demonstrating that a nominal GDP targeting rule implemented through money supply could be the most effective monetary policy regime. Furthermore, our analysis indicates that a robust, active fiscal policy regime, combined with nominal GDP targeting, could significantly enhance economic stabilization efforts.

We believe that our manuscript aligns with the scope and interests of "Applied Economics" and would make a meaningful contribution to the field. We are confident that the insights presented in our research will be of interest to your readership. Please address all correspondence concerning this manuscript to me at ziqing.wang@shu.ac.uk

Thank you for considering our submission.

Sincerely,

Vo Phuong Mai Le
David Meenagh
Patrick Minford
Ziqing Wang

8 Funding

There is no funding to declare.

References

[1] Armington, P.S., 1969. A theory of demand for products distinguished by place of production. Staff Papers, 16(1), pp.159-178.

[2] Baumeister, Christiane & Luca Benati. 2013. Unconventional Monetary Policy and the Great Recession: Estimating the Macroeconomic Effects of a Spread Compression at the Zero Lower Bound. International Journal of Central Banking, 9(2):165-212.

[3] Bernanke, B.S., Gertler, M.G. and Gilchrist, S., 1999. S.(1999):"The Financial Accelerator in a Quantitative Business Cycle Framework.". The Handbook of Macroeconomics, 1, pp.1342-1385.

[4] Bernanke, B.S., 2017. Monetary policy in a new era. Evolution or Revolution?: Rethinking Macroeconomic Policy after the Great Recession, pp.3-48.

[5] Boehl, G., Goy, G., & Strobel, F. (2022). A structural investigation of quantitative easing. Review of Economics and Statistics, 1-45.

[6] Calvo, G.A., 1983. Staggered prices in a utility-maximizing framework. Journal of monetary Economics, 12(3), pp.383-398.

[7] Carlstrom, C. T., Fuerst, T. S., & Paustian, M. (2017). Targeting long rates in a model with segmented markets. American Economic Journal: Macroeconomics, 9(1), 205-242.

[8] Chen, H., Cúrdia, V. and Ferrero, A., 2012. The macroeconomic effects of large-scale asset purchase programmes. The economic journal, 122(564), pp.F289-F315.

[9] Coibion, O., Gorodnichenko, Y. and Wieland, J., 2012. The optimal inflation rate in New Keynesian models: should central banks raise their inflation targets in light of the zero lower bound?. Review of Economic Studies, 79(4), pp.1371-1406.

[10] Curdia, V., & Woodford, M. (2010). Credit spreads and monetary policy. Journal of Money, Credit and Banking, 42, 3-35.

[11] Dittmar, R., Gavin, W.T. and Kydland, F.E., 1999. Price-level uncertainty and inflation targeting. Review-Federal Reserve Bank of Saint Louis, 81, pp.23-34.

[12] Dittmar, R. and Gavin, W.T., 1999. What do New Keynesian Phillips curves imply for price level targeting? (No. 1999-021). Federal Reserve Bank of St. Louis.

[13] Eggertsson, G.B., 2003. Zero bound on interest rates and optimal monetary policy. Brookings papers on economic activity, 2003(1), pp.139-233.

[14] Fabo, B., Jančoková, M., Kempf, E., & Pástor, Ľ. (2021). Fifty shades of QE: Comparing findings of central bankers and academics. Journal of Monetary Economics, 120, 1-20.

[15] Frankel, J., 2012. The death of inflation targeting. Project syndicate, 16.

[16] Gagnon, J., Raskin, M., Remache, J. and Sack, B., 2018. The financial market effects of the Federal Reserve's large-scale asset purchases. 24th issue (Mar 2011) of the International Journal of Central Banking.

[17] Gertler, M. and Kiyotaki, N., 2010. Financial intermediation and credit policy in business cycle analysis. In Handbook of monetary economics (Vol. 3, pp. 547-599). Elsevier.

[18] Gertler, M. and Karadi, P., 2011. A model of unconventional monetary policy. Journal of Monetary Economics, 58(1), pp.17-34.

[19] Gertler, M. and Karadi, P., 2018. Qe 1 vs. 2 vs. 3...: A framework for analyzing large-scale asset purchases as a monetary policy tool. 29th issue (January 2013) of the International Journal of Central Banking.

[20] Gourieroux, C., Monfort, A. and Renault, E., 1993. Indirect inference. Journal of applied econometrics, 8(S1), pp.S85-S118.

[21] Gourieroux, C. and Monfort, A., 1995. Statistics and econometric models (Vol. 1). Cambridge University Press.

[22] Hamilton, J.D. and Wu, J.C., 2012. The effectiveness of alternative monetary policy tools in a zero lower bound environment. Journal of Money, Credit and Banking, 44, pp.3-46.

[23] Hatcher, M. and Minford, P., 2014. Inflation targeting vs price-level targeting: A new survey of theory and empirics. Vox.

[24] Joyce, M., Tong, M. and Woods, R., 2011. The United Kingdom's quantitative easing policy: design, operation and impact. Bank of England Quarterly Bulletin.

[25] Kapetanios, G., Mumtaz, H., Stevens, I. and Theodoridis, K., 2012. Assessing the economy-wide effects of quantitative easing. The Economic Journal, 122(564), pp.F316-F347.

[26] Koenig, E.F., 2013. Like a good neighbour: Monetary policy, financial stability, and the distribution of risk. International Journal of Central Banking, 9(2), pp.57-82.

[27] Krishnamurthy, A. and Vissing-Jorgensen, A., 2011. The effects of quantitative easing on interest rates: channels and implications for policy (No. w17555). National Bureau of Economic Research.

[28] Krugman, P.R., Dominquez, K.M. and Rogoff, K., 1998. It's baaack: Japan's slump and the return of the liquidity trap. Brookings Papers on Economic Activity, 1998(2), pp.137-205.

[29] Le, V.P.M., Meenagh, D. and Minford, P., 2012. What causes banking crises? An empirical investigation.

[30] Le, V.P.M., Meenagh, D., Minford, P. and Wickens, M., 2012. Testing DSGE models by Indirect inference and other methods: some Monte Carlo experiments.

[31] Le, V.P.M., Meenagh, D. and Minford, P., 2016. Monetarism rides again? US monetary policy in a world of Quantitative Easing. Journal of International Financial Markets, Institutions and Money, 44, pp.85-102.

[32] Lyu, J., Le, V. P. M., Meenagh, D., & Minford, P. (2023). UK monetary policy in an estimated DSGE model with financial frictions. Journal of International Money and Finance, 130, 102750.

[33] Meenagh, D., Minford, P. and Wickens, M., 2009. Testing a DSGE model of the EU using indirect inference. Open Economies Review, 20(4), pp.435-471.

[34] Neely, C.J., 2010. The large scale asset purchases had large international effects (pp. 1-45). Federal Reserve Bank of St. Louis, Research Division.

[35] Sheedy, K.D., 2014. Debt and incomplete financial markets: A case for nominal GDP targeting. Brookings Papers on Economic Activity, 2014(1), pp.301-373.

[36] Smets, F. and Wouters, R., 2007. Shocks and frictions in US business cycles: A Bayesian DSGE approach. American economic review, 97(3), pp.586-606.

[37] Sims, E. and Wu, J.C., 2021. Evaluating central banks' tool kit: Past, present, and future. Journal of Monetary Economics, 118, pp.135-160.

[38] Taylor, J.B., 1995. The monetary transmission mechanism: an empirical framework. Journal of Economic Perspectives, 9(4), pp.11-26.

[39] Tobin, J., 1969. A general equilibrium approach to monetary theory. Journal of Money, Credit and Banking, 1(1), pp.15-29.

[40] Vila, J.L. and Vayanos, D., 2009. A Preferred-Habitat Model of the Term Structure of Interest Rates (No. dp641). Financial Markets Group.

[41] Walentin, K., 2014. Business cycle implications of mortgage spreads. Journal of Monetary Economics, 67, pp.62-77.

[42] Weale, M., & Wieladek, T. (2016). What are the macroeconomic effects of asset purchases?. Journal of Monetary Economics, 79, 81-93.

Appendices

A Augmenting the BGG model for collateral and money

The BGG model is extended with two key assumptions: banks require collateral as a proportion of net worth , and liquidating this collateral incurs a cost of δ per unit. The model comprises three main components: a bankruptcy threshold where firms decide whether to default, the zero profit condition for banks, and the maximization of firms' utility given the constraints imposed by the first two components.

At the bankruptcy threshold (ω), firms are indifferent between defaulting and staying in business. If bankrupt, firms lose $(1 + R^K)\omega A + cN$ and gain ZB, where $Z = 1 +$ credit rate and $B =$ bank borrowing. Thus, $ZB = (1 + R^K)\omega A + cN$. Given the balance sheet $B = A - N + cN$ and leverage $L = A/N$, we obtain:

$$Z = \frac{(1 + R^K)\omega L + c}{L - 1 + c} \tag{1}$$

Banks' zero profit condition is:

$$[1 - F(\omega)]ZB + (1 - \mu)G(\omega)(1 + R^K)A + cNF(\omega)(1 - \delta) = (1 + R)B \tag{2}$$

Substituting from the bankruptcy threshold and balance sheet, we get:

$$[1-F(\omega)](1+R^K)\omega A+(1-\mu)G(\omega)(1+R^K)A+cN(1-\delta F(\omega)) = (1+R)(A-N+cN) \tag{3}$$

Let $\Gamma(\omega) = [1 - F(\omega)]\omega + G(\omega)$, then:

$$[\Gamma(\omega) - \mu G(\omega)](1 + R^K)L = (1 + R)(L - 1) + c(1 + R - 1 + \delta F(\omega)) \tag{4}$$

This simplifies to the banks' leverage offer curve:

$$L = \frac{1 + R - c[R + \delta F(\omega)]}{1 + R - \Psi(\omega)(1 + R^K)} \tag{5}$$

where $\Psi(\omega) = \Gamma(\omega) - \mu G(\omega)$. This curve is upward-sloping and convex.

To obtain the overall contract, firms' utility (returns) relative to their cost of funds is maximized:

$$\int_{\omega}^{\infty} \frac{(1 + R^K)\omega A + cN - ZB}{N(1 + R)} dF(\omega) \tag{6}$$

From the bankruptcy threshold, substituting $ZB = (1 + R^K)\omega A + cN$, the overall returns become:

$$\int_{\omega}^{\infty} \frac{(1 + R^K)(\omega - \omega)A}{N(1 + R)} dF(\omega) = \frac{(1 + R^K)}{(1 + R)} L[1 - \Gamma(\omega)] \tag{7}$$

Maximizing this utility function subject to the leverage offer curve:

$$L = \frac{1 + R - c[R + \delta F(\omega)]}{1 + R - \Psi(\omega)(1 + R^K)} \tag{8}$$

we solve for the firm's optimal choice of ω as:

$$\{1+R-c[R+\delta F(\omega)]\}\{1+R-\Phi'(1+R^K)\} = \{-c\delta F'(\omega)[1-\Gamma(\omega)]/\Gamma'(\omega)\}\{1+R-\Psi(\omega)(1+R^K)\} \tag{9}$$

where $\Phi' = \Psi'(\omega)/\Gamma'(\omega) + (1 - \Psi'(\omega)/\Gamma'(\omega))\Psi(\omega) \approx 1$.

Finally, to evaluate the effect of δ on equilibrium values of R^K and ω, we consider M_0 injections, which reduce δ. This leads to:

$$dR^K/d\delta > 0 \tag{10}$$

Thus, increasing M_0 lowers the required return on capital and the credit premium, illustrating its role in monetary policy by reducing financial frictions.

B DSGE model list (log-linearised)

In this part, to describe the whole framework, we list all the model equations in the log-linearized form. Each equation is normalized with one endogenous variable. All the variables are in natural logarithm format, apart from variables that are already in the form of percentages and ratios.

Consumption Euler equation

$$C_t = C_1 C_{t-1} + C_2 E_t C_{t+1} + C_3(L_t - E_t L_{t+1}) - C_4(r_t - E_t \pi_{t+1}) + eb_t$$

$$C_1 = \frac{\frac{\lambda}{\gamma}}{1+\frac{\lambda}{\gamma}}, \quad C_2 = \frac{1}{1+\frac{\lambda}{\gamma}}, \quad C_3 = \frac{(\sigma_c - 1)\frac{w_*^h L_*}{C_*}}{(1+\frac{\lambda}{\gamma})\sigma_c}, \quad C_4 = \frac{1-\frac{\lambda}{\gamma}}{(1+\frac{\lambda}{\gamma})\sigma_c}$$

Real Unconverted Interest Rate Parity

$$E_t q_{t+1} - q_t = (r_t - E_t \pi_{t+1}) - (r_t^f - E_t \pi_{t+1}^f)$$

Labor Demand Equation

$$l_t = -w_t + \left(1 + \frac{1-\psi}{\psi}\right) rk_t + k_{t-1}$$

External Finance Premium Equation without QE

$$E_t cy_{t+1} - (r_t - E_t \pi_{t+1}) = \chi(qq_t + k_t - n_t) + \xi_t + epr_t$$

External Finance Premium Equation with QE

$$E_t cy_{t+1} - (r_t - E_t \pi_{t+1}) = \chi(qq_t + k_t - n_t) - \psi m_t + \xi_t + epr_t$$

Net Worth Evolution Equation

$$n_t = \frac{N}{k}(cy_t - E_{t-1} cy_t) + E_{t-1} cy_t + \theta n_{t-1} + enw_t$$

Capital Services Equation

$$k_t^s = k_{t-1} + z_t$$

Capital Utilisation Equation

$$z_t = \frac{1-\psi}{\psi} rk_t$$

Hybrid Wage Equation

$$w_t^{NK} = \frac{\beta\gamma^{1-\sigma_c}}{1+\beta\gamma^{1-\sigma_c} l_p} E_t w_{t+1} + \frac{1}{1+\beta\gamma^{(1-\sigma_c)} l_p} w_{t-1} + \frac{\beta\gamma^{1-\sigma_c}}{1+\beta\gamma^{1-\sigma_c}} E_t \pi_{t+1} - \frac{1+\beta\gamma^{1-\sigma_c} l_w}{1+\beta\gamma^{1-\sigma_c}} \pi_t$$
$$- \frac{l_w}{1+\beta\gamma^{1-\sigma_c}} \pi_{t-1} - \frac{1}{1+\beta\gamma^{1-\sigma_c}} \left(\frac{(1-\beta\gamma^{1-\sigma_c}\xi_w)(1-\xi_w)}{\xi_w(1+(\phi_p - 1)\epsilon_w)} (w_t - \sigma_l l_t - \left(\frac{1}{1-\frac{h}{\gamma}}\right)(c_t - \frac{h}{\gamma} c_{t-1})) \right) + ew_t$$

$$w_t^{NC} = \sigma_l l_t - \left(\frac{1}{1-\frac{h}{\gamma}}\right)(c_t - \frac{h}{\gamma} c_{t-1}) - (\pi_t - E_{t-1}\pi_t) + ew_t^s$$

$$w_t^{hybrid} = w^w w_t^{NK} + (1 - w^w) w_t^{NC}$$

Hybrid Keynesian Phillips Curve

$$\pi_t^{NK} = \frac{\beta\gamma^{1-\sigma_c}}{1+\beta\gamma^{1-\sigma_c} l_p} E_t \pi_{t+1} + \frac{l_p}{1+\beta\gamma^{(1-\sigma_c)} l_p} \pi_{t-1}$$

$$-\frac{1}{1+\beta\gamma^{1-\sigma_c}l_p}\left(\frac{(1-\beta\gamma^{1-\sigma_c}\xi_p)(1-\xi_p)}{\xi_p(1+(\phi_p-1)\epsilon_p)}(ar_t^k+(1-\alpha)w_t)\right)-ep_t$$

$$\pi_t^{NC}=(1-\alpha)w_t+\alpha r_t^k$$

$$\pi_t^{hybrid}=w^w\pi_t^{NK}+(1-w^w)\pi_t^{NC}$$

Tobin Q Equation

$$qq_t=\frac{1-\sigma}{1-\sigma+R_*^k}E_tqq_{t-1}+\frac{R_t^k}{1-\sigma+R_*^k}E_trk_{t+1}-E_tcy_{t+1}$$

Investment Euler Equation

$$I_t=\frac{1}{1+\beta\gamma^{(1-\sigma_c)}}I_{t-1}+\frac{\beta\gamma^{1-\sigma_c}}{1+\beta\gamma^{1-\sigma_c}}E_tI_{t+1}+\frac{1}{(1+\beta\gamma^{(1-\sigma_c)})\gamma^2\varphi}qq_t+ei_t$$

Production Function

$$y_t=\phi[\alpha k_t^s+(1-\alpha)l_t+ea_t]$$

Taylor Rule Equation

$$r_t=\rho r_{t-1}+(1-\rho)(r_p\pi_t+r_yy_t)+r_{\delta y}(y_t-y_{t-1})+er_t$$

Quantitative Easing with ZLB crisis

$$m_t=m_{t-1}+\psi_2(cy_t-cy_*)+errm_{t,zlb},\quad r_t\leq 0.0625$$

Money supply equation without QE

$$m_t=m_{t-1}+\psi_1(M_t-M_{t-1})+errm_t,\quad r_t>0.0625$$

M2 Equation

$$M_t=(1+\nu-\mu)k_t+\mu m_t-\nu n_t$$

Foreign Bond Evolution Equation

$$b_t^f=(1+r_t^f)d_{t-1}^f+\frac{EX}{Y}\frac{P_*^d}{Q_*}ex_t+\frac{EX}{Y}\frac{P_*^d}{Q_*}q_t-\frac{IM}{Y}m_t$$

Export Equation

$$x_t=c_t^f+\frac{1}{\omega}\sigma^fq_t+eex_t$$

Import Equation

$$m_t=c_t-\sigma q_t+eim_t$$

Resource Constraint

$$y_t=\frac{c}{y}c_t+\frac{i}{y}i_t+\frac{k}{y}R^kz_t+\frac{c^e}{y}c_t^e+\frac{x}{y}x_t-\frac{m}{y}m_t+eg_t$$

Stochastic Shock Process

To determine the dynamics of the model, we set up 15 shocks including two exogenous variables, foreign consumption C_t^f and foreign interest rate r_t^f. The shock process is listed as follows:

Government spending shock (market clearing equation)

$$eg_t = \rho_1 eg_{t-1} + \rho_2 \eta_t^3 + \eta_t^1$$

Preference shock (consumption Euler equation)

$$eb_t = \rho_2 eb_{t-1} + \eta_t^2$$

Productivity shock (production function)

$$(ea_t - ea_{t-1}) = \rho_3(ea_{t-1} - ea_{t-2}) + \eta_t^3$$

Investment shock (Investment Euler equation)

$$ei_t = \rho_4 ei_{t-1} + \eta_t^4$$

Monetary policy shock (Taylor rule equation)

$$er_t = \rho_5 er_{t-1} + \eta_t^5$$

Price mark-up shock (Hybrid inflation rate equation)

$$ep_t = \rho_6 ep_{t-1} + \eta_t^6$$

Wage mark-up shock (Hybrid wage equation for NK)

$$ew_t = \rho_7 ew_{t-1} + \eta_t^7$$

External finance premium shock (External finance premium equation)

$$epr_t = \rho_9 epr_{t-1} + \eta_t^9$$

Net worth shock (Net Worth equation)

$$enw_t = \rho_{10} enw_{t-1} + \eta_t^{10}$$

Money supply shock (M0 equation with crisis)

$$errm_t = \rho_{11} errm_{t-1} + \eta_t^{11}$$

Money supply shock (M0 equation without crisis)

$$errm_t = \rho_{12} errm_{t-1} + \eta_t^{12}$$

Export demand shock (Export demand equation)

$$eex_t = \rho_{13} eex_{t-1} + \eta_t^{13}$$

Import demand shock (Import demand equation)

$$eim_t = \rho_{14} eim_{t-1} + \eta_t^{14}$$

Exogenous foreign consumption process

$$c_t^f = \rho_{15} c_{t-1}^f + \eta_t^{15}$$

Exogenous foreign interest rate process

$$r_t^f = \rho_{16} r_{t-1}^f + \eta_t^{16}$$

C Data and Resources

D Stationarity of shocks

Symbol	Variable	Definition, Description	Sources
R	Nominal interest rate	3 month average sterling T-bill	BoE
I	Investment	Gross fixed capital formation + Changes in inventories	ONS
P^k	Price of capital	Calculated from model equation	N/A
K	Capital	Calculated from model equation	N/A
π	Inflation	Quarterly percentage change in price GDP deflator	ONS
W	Wage	Average wage and earning / Total actual working hours, divided by GDP deflator	ONS
C	Consumption	Household final consumption expenditure	ONS
Y	Output	Gross domestic product	ONS
L	Labour	Employment / Total actual hours worked	ONS
$Rrental$	Rental rate of capital	Calculated from equation	N/A
S	External finance premium	Difference of bank lending rate and risk-free rate	BoE
N	Net worth	FTSE all share index, divided by GDP deflator	Data Stream
M0	Quantitative easing	M0 Stock in UK	Federal Reserve Economic Data
M2	Total money supply	M2 money stock in UK	Federal Reserve Economic Data
EX	Export	Total UK export	ONS
IM	Import	Total UK import	ONS
Q	Real exchange rate	Inverse of quarterly average sterling effective exchange rate	ONS
P	General price level	Consumer Price Index of All items in the UK	Federal Reserve Economic Data

Table 9 Data and Resources

Shocks	**ADF p-value**[a]	**KPSS Statistic**[b]	**AR(1) Parameters**	**Process**
Government spending	0.0324**	0.1285	0.9022	Trend Stationary
Preferences shock	0.0000*	0.3833	0.8211	Stationary
Investment shock	0.0038***	0.1871	-0.1105	Stationary
Monetary policy shock	0.0001**	0.3027	-0.0560	Stationary
Productivity shock	0.7327	1.0547***	-0.0905	Non-Stationary
Price mark-up shock	0.0000***	0.090	-0.2713	Stationary
Wage mark-up shock	0.0000***	0.3136	-0.2713	Stationary
Premium shock	0.070*	0.2275	0.7961	Trend Stationary
Networth shock	0.0541*	0.1510	0.5939	Stationary
Mzero shock (M0 eq)	0.0000***	0.4072	0.0267	Stationary
Mzero shock (crisis)	0.0000***	0.3916	0.0275	Stationary
Export shock	0.0420**	0.3262	0.8083	Trend Stationary
Import shock	0.002***	0.2636	0.9553	Trend Stationary

Table 10 Stationarity of shocks

[a] Augmented Dickey-Fuller (ADF) test, ***, **,* indicate rejection of the null hypothesis (with unit root) at the 10%, 5%, and 1% significance levels, respectively.

[b] Kwiatkowski-Phillips-Schmidt-Shin (KPSS) test, ***, **,* indicate rejection of the null hypothesis (stationary) at the 10%, 5%, and 1% significance levels, respectively.