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# Cardiff Economics Working Papers



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*Haixia Chen, Vo Phuong Mai Le, David Meenagh and  
Patrick Minford*

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Cardiff Business School  
Cardiff University  
Colum Drive  
Cardiff CF10 3EU  
United Kingdom  
t: +44 (0)29 2087 4000  
f: +44 (0)29 2087 4419  
[business.cardiff.ac.uk](http://business.cardiff.ac.uk)

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Enquiries: [EconWP@cardiff.ac.uk](mailto:EconWP@cardiff.ac.uk)

# UK Monetary Policy in An Estimated DSGE Model with State-Dependent Price and Wage Contracts\*

Haixia Chen<sup>†</sup>

Vo Phuong Mai Le<sup>‡</sup>

David Meenagh<sup>§</sup>

Patrick Minford<sup>¶</sup>

Considerable micro-level evidence suggests that price/wage contract durations fluctuate with the state of the economy, particularly inflation; nonetheless, macro-level evidence for this is scarce. We incorporate state-dependent price/wage setting into an open economy DSGE model to investigate the evidence of state-dependence in the UK economy's post-war behaviour. The model is estimated and tested using the Indirect Inference method and is found to fit the dynamic behaviour of key variables very well over a long sample period 1955-2021. In the state-dependent scenario, apart from the direct responses to shocks, monetary policy affects the degree to which the economy is close to the NK world, which in turn indirectly affects the response to these shocks; it also potentially pushes interest rates to the Zero Lower Bound, ZLB. Under the interaction of state-dependence and the ZLB, monetary-fiscal coordination is needed to stabilise the economy, as monetary policy alone cannot achieve economic stability during ZLB scenarios, where it must use bond purchases (Quantitative Easing, QE). Our findings suggest that a coordinated monetary-fiscal policy framework, i.e., an interest rate policy that targets nominal GDP complemented by a ZLB-suppressing fiscal policy, decreases the frequency of economic crises and enhances price/output stability and household welfare compared to the baseline Taylor Rule and QE framework.

**keywords:** State-dependence, DSGE, QE, ZLB, Monetary Policy, Nominal GDP Targeting, Fiscal Policy, Indirect Inference.

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<sup>†</sup>Cardiff Business School, Cardiff University. Email: Chenh53@cardiff.ac.uk (Corresponding author)

<sup>‡</sup>Cardiff Business School, Cardiff University. Email: LeVP@cardiff.ac.uk

<sup>§</sup>Cardiff Business School, Cardiff University. Email: MeenaghD@cardiff.ac.uk

<sup>¶</sup>Cardiff Business School, Cardiff University, and CEPR. Email: MinfordP@cardiff.ac.uk

# 1 Introduction

Micro-founded models of price/wage-setting behaviour are crucial for understanding the dynamics of macroeconomic variables and for assessing the performances of alternative monetary policies. It is widely debated whether prices and wages respond flexibly to changes in economic conditions or whether they are set for fixed durations. The prevailing paradigm of monetary economics, the New Keynesian (NK) model, uses the [Calvo \(1983\)](#) model of time-dependent price and wage stickiness. Under a Calvo contract, a homogeneous firm/labour union has a fixed probability of changing its price/wage in each period, equivalent to a fixed duration contract. The classical theory emphasises that prices/wages are fully flexible and that its contract equivalents are fully state-contingent contracts; thus, agents could achieve optimal outcomes. However, given the existence of menu costs, it may be optimal for agents to ignore small shocks and maintain prices unchanged for some duration, as the cost of changing prices may exceed the cost of the shocks in this case. The cost of shocks they would ignore in such a way and the duration they would be willing to keep prices constant would be state-dependent. In contrast, when the cost of not responding to the shocks is higher than the cost of these shocks, it would be optimal for the agents to adjust the prices. Therefore, this is different from the classical assumption of fully flexible prices and fully state-dependent contracts. In other words, the price contract durations are state-dependent, but not fully flexible in the presence of the menu costs. Similarly, state-dependent wage contracts are based on the idea that the fixed costs of renegotiating employment contracts prevent frequent wage adjustments; and these fixed costs mean that the probability and the magnitude of wage changes vary with the state of the economy.

The nature of price/wage setting has a crucial implication for monetary policy. The effectiveness of monetary policy in stabilising the business cycles depends on the flexibility of the price level. Flexible price adjustments will absorb shocks and largely dampen the impact of monetary shocks. Conversely, when prices show a high level of stickiness, monetary shocks can have a pronounced effect on output, thus facilitating the stabilisation of business cycles. With respect to wage adjustment, whether wages are set to be state-dependent or time-dependent also has different implications for the effects of monetary policy. When wages are time-dependent, the impact of monetary policy on both employment and output is substantial. Nevertheless, state-dependent wage contracts indicate a less prominent impact, as part of the shocks are absorbed through wage adjustments, resulting in a significant impact on wage fluctuations.

A substantial amount of evidence from micro-level studies in different countries suggests that the durations of price/wage contracts fluctuate with the state of the economy, particularly inflation. However, there has been a scarcity of macroeconomic literature that incorporates this state-dependence into DSGE models. The aim of this paper is to in-

investigate whether there is macro-level evidence to corroborate the micro-level evidence of state-dependence in the UK, and to examine the policy implications of state-dependence. We develop an open economy DSGE model that integrates a state-dependent price/wage-setting framework, based on the work of [Le et al. \(2021\)](#). Therefore, our model comprises the following sophisticated aspects. It extends the [Smets and Wouters \(2007\)](#) (SW07) model by combining the NK and New Classical (NC) models into a hybrid model, adds the [Bernanke et al. \(1999\)](#) (BGG) banking sector, and incorporates the new monetary developments following the recent Great Financial Crisis (GFC), i.e., the Zero Lower Bound (ZLB) and Quantitative Easing (QE). Regarding the extension of the model to an open economy, our foreign block builds on the spirit of [Lyu et al. \(2023\)](#) and [Gali and Monacelli \(2005\)](#), introducing exchange rates, foreign bonds, exports and imports. This suggests a distinction between the CPI and the price index of goods produced domestically. Furthermore, the trade equation is introduced via the [Armington \(1969\)](#) bundle, which aggregates domestic and foreign contributions to final consumption. The capital account of the balance of payments operates based on uncovered interest parity between domestic and foreign bonds - an assumption that passes Indirect Inference tests in complete models for the majority of ten country pairs with the US, the UK among them ([Minford et al., 2022](#)). Finally and most significantly, our model incorporates state-dependence. In this hybrid model, a fraction of goods markets are assumed to have flexible prices while the rest have sticky prices. Similarly, a fraction of labour markets are flexible in setting wages whilst the remainder face nominal rigidities. To embed state-dependence, we assume that the fraction of firms/unions with nominal rigidity is state-dependent and related to past inflation. In contrast, in models with fixed price/wage durations, the fraction of flexible sectors is assumed to be fixed.

This paper estimates and tests a state-dependent DSGE model on unfiltered UK macroeconomic data over the period 1955Q1-2021Q1 using the simulation-based Indirect Inference method. The main findings and contributions of this study are that the state-dependent model fits the dynamic behaviour of the key variables over the sample period, with the price/wage contract durations fluctuating with the state of the economy (inflation) throughout the whole sample period. Regarding the policy implications in the presence of state-dependence, we find that a coordinated monetary-fiscal policy framework, i.e., Nominal GDP targeting complemented by a ZLB-suppressing fiscal policy, implying a modest rise in interest rate variability, outperforms the baseline framework of the Taylor Rule with QE in terms of its ability to avoid crises and decrease welfare costs. This alternative framework stabilises both inflation and output more strongly under demand shocks than the baseline framework. Though it worsens the output response by stabilising current inflation more under supply shocks, our model suggests that this framework generally enhances the stability of both output and inflation, given that demand shocks predominantly drive output fluctuations. Additionally, it significantly stabilises

inflation, which in turn stabilises price/wage durations, leading to long price/wage durations. To the best of our knowledge, this paper is the first macro-level empirical study of state-dependent price/wage contracts in an open economy context.

The rest of this paper is organised as follows. Section 2 provides a literature review. Section 3 sets up a state-dependent DSGE model in which both price and wage contracts change endogenously with the state of the economy rather than merely being time-dependent. Specifically, price/wage durations depend on the variance of lagged inflation, which in turn depends on durations. Section 4 briefly discusses the Indirect Inference method and the data used. Section 5 presents the empirical results. Section 6 analyses policy implications. Section 7 concludes the paper.

## 2 Literature Review

Micro-level empirical studies conducted for different countries across varying periods of data have shown state-dependent price/wage adjustments, especially state-dependent pricing. However, the state-dependent contracts at the macro-level have been relatively unexplored, with only a few empirical studies incorporating them into closed economy DSGE models, all of which focus on the US. This highlights a distinct gap in the extant literature, specifically in the context of open economies.

In recent years, a growing body of literature at the micro-level has shown state-dependent pricing, see [Bhattarai and Schoenle \(2014\)](#) and [Nakamura et al. \(2018\)](#) for the US, [Wulfsberg \(2016\)](#) and [Nilsen et al. \(2018\)](#) for Norway, [Dedola et al. \(2021\)](#) for Denmark, [Rudolf and Seiler \(2022\)](#) for Switzerland, [Alvarez et al. \(2019\)](#) for Argentina, [Konieczny and Skrzypacz \(2005\)](#) for Poland, and [Gagnon \(2009\)](#) for Mexico.

Micro-level evidence of state-dependent pricing has also been found in the UK. [Bunn and Ellis \(2012a\)](#) investigated UK consumer price behaviour and found that the probability of a price change did not remain fixed over time but varied between years and months. Furthermore, there was evidence of a correlation between the probability of monthly price increase and headline inflation over the period 1996-2006, but less evidence of a link between the probability of price decrease and inflation. [Bunn and Ellis \(2012b\)](#) examined monthly UK producer price behaviour over the period 2003-2007 and showed that the probability of price changes was not fixed. [Zhou and Dixon \(2019\)](#) explored price-setting behaviour in the UK using Consumer Price Index (CPI) and Producer Price Index microdata during the Great Moderation period 1996-2007, revealing that prices were indeed fixed for average durations, but they were state-dependent. [Dixon et al. \(2020\)](#) examined the impact of the GFC on firm's pricing behaviour using UK CPI microdata for the period 1996-2013 and found strong evidence of a relationship between the frequency of price change and inflation, with inflation tending to increase the frequency of price changes, primarily by increasing the frequency of price increases. [Petrella et al. \(2018\)](#)

used monthly micro price data underlying the UK CPI from 1996-2017 and showed a considerable degree of positive co-movement between price changes and inflation. Moreover, they illustrated that state-dependence plays a crucial role in price setting; when inflation is high and volatile, the extensive margin of price adjustment (adjustments driven by shocks rather than pre-determined price adjustments) becomes prominent. More recently, [Davies \(2021\)](#) examined a large-scale micro-dataset of 41 million UK consumer prices to provide monthly facts on price-setting behaviour over the period 1988-2020, a sample period with a volatile economic environment including the Exchange Rate Mechanism (ERM) crisis, the 2008 GFC and the 2016 EU referendum, as well as the coronavirus pandemic. They found that state-dependent models, rather than time-dependent pricing models, were consistent with the behaviour of UK firms. Regarding pricing, the coronavirus pandemic had a more severe impact than the GFC, with a surge in the frequency of price change including both upward and downward price movements.

With respect to state-dependent wage adjustments, there is a relatively limited number of studies investigating this compared to the literature on state-dependent pricing. [Sigurdsson and Sigurdardottir \(2016\)](#) examined administrative microdata from the Icelandic labour market over the period 1998-2010. They found evidence of time-dependent wage changes and also strong evidence of state-dependence, as the timing of wage adjustments was determined by both cumulated inflation and unemployment over current and past wage spells, in addition to an increase in the frequency of nominal wage cuts following large macroeconomic shocks. Consistent evidence has been found by [Grajales et al. \(2019\)](#), who studied administrative data at the employee level over the period 2006-2021 for the Netherlands and showed a mixture of time- and state-dependent wage behaviour, with inflation and unemployment being important determinants of the probability of wage adjustment. [Grigsby et al. \(2021\)](#) used US microdata from 2008-2016 and found strong evidence of downward nominal base wage rigidity for employees who continuously worked for the same firm (referred to as job-stayers), with the nominal base wage duration being around six quarters. They documented time-dependent wage adjustments, with most adjustments occurring one year after the last adjustment. However, they also emphasized evidence of state-dependence, as 6% of workers experienced nominal base wage cuts during the Great Recession, although wage cuts were extremely rare for job-stayers. Their findings suggested that any model with a fixed wage adjustment would struggle to match the patterns of wage setting during severe business cycles. More recently, [Cajner et al. \(2020\)](#) investigated the behaviour of the US labour market in the first four months of the coronavirus pandemic and demonstrated that wage adjustments during the pandemic were large relative to the prior recessions. Concerning the UK, the labour market is flexible compared to most other European countries ([Millard and Tatomir, 2015](#)), and exhibits a low degree of both downward nominal and real wage rigidity ([Dickens et al., 2007](#)). [Millard and Tatomir \(2015\)](#) conducted a wage-setting survey over the period 2010-



2013 for the UK and found that the median frequency of wage-setting was once a year and that around 30% of firms directly and explicitly linked wage changes to inflation.

The abundant micro-level evidence on state-dependence has motivated recent macro-level studies to attempt to replicate this state-dependence using macroeconomic models. [Gasteiger and Grimaud \(2020\)](#) constructed an NK model with a state-dependent price-setting framework in which the decisions to change prices depend on expected costs and benefits; hence a firm will adjust its price optimally only when its expected benefits outweigh its expected costs. They found that the augmented NK model was consistent with price setting frequency based on microdata and can explain the dynamics of inflation to a significant extent. Moreover, their state-dependent framework improved the macroeconomic time series fit of the NK model for the US sample period 1959-2019. However, they only included state-dependent pricing and assumed time-dependent wage setting. According to [Costain et al. \(2019\)](#) and [Sigurdsson and Sigurdardottir \(2016\)](#), a model that incorporates state-dependent price setting but maintains time-dependent wage setting may not accurately measure the impact of monetary changes on real variables and may lead to false conclusions. To the best of our knowledge, only a limited number of studies have included both state-dependent price adjustment and state-dependent wage adjustment within DSGE models, and they all focused on the US, see [Takahashi \(2018\)](#), [Costain et al. \(2019; 2022\)](#) and [Le et al. \(2021\)](#).

[Takahashi \(2018\)](#) developed a DSGE model that incorporates state-dependence in both prices and wages. In this model, the state-dependent pricing framework is based on the stochastic menu cost model of [Dotsey et al. \(1999\)](#). The state-dependent wage setting is endogenously subject to fixed wage adjustment costs that are stochastic and heterogeneous across households, hence endogenously generating staggered nominal wage adjustments. [Takahashi \(2018\)](#) calibrated the distribution of wage setting cost to match the US data on the proportion of wages that remained unchanged for a year and found that the state-dependent wage setting model produced responses to monetary shocks similar to those from the time-dependent model. [Costain et al. \(2019; 2022\)](#) investigated a DSGE model that incorporates state-dependent price/wage setting based on a control cost model, where price and wage decisions are costly and random variables. Price/wage setters are assumed to be subject to control costs and make optimal decisions about when and how to reset their prices/wages. The cost increases with the precision of price/wage decisions. By calibrating the microdata evidence of the frequency of price/wage changes in the DSGE model, where durations depend on inflation, they found that sticky wages play a critical role in the effects of monetary policy on output, as the version of their model exclusively including sticky wages can generate almost as much in the way of output effects as the version with both wage and price stickiness. Furthermore, the model with both sticky prices and wages had a larger real effect of monetary shocks than the model with only price stickiness. According to [Le et al. \(2021\)](#), the studies by [Takahashi \(2018\)](#)



and Costain et al. (2019; 2022) used microdata from a stable inflation sample period – the Great Moderation. This may be why their macro models turn out to be similar to the US model of Smets and Wouters (2007).

Our study draws inspiration from a series of studies of the US economy conducted by Le et al. (2011; 2016a; 2021). Le et al. (2011) estimated a hybrid DSGE model with fixed price/wage durations using the Indirect Inference method and found that the model fitted the behaviour of the data for 1984-2004, but was rejected by the data behaviour for the whole post-war period 1947-2004. Le et al. (2016a) extended the Le et al. (2011) model to allow for financial frictions, the ZLB and QE, and showed that the extended model fitted the data behaviour well from the Great Moderation to 2011. Le et al. (2021) suggested that the failure of their fixed-duration model to pass the test for the full post-war sample may be attributed to changes in wage/price-setting behaviour over time in response to fluctuations in the macro environment; in particular, there were several significant inflationary episodes during the sample period. Therefore, the authors extended the model to include state-dependence in price/wage durations and re-estimated the model for the full post-war period. Their findings suggest that the model with this extension can match the data behaviour well for the full sample period. Furthermore, they found strong NK periods during the Great Moderation, with more flexible price periods during the Great Inflation and the Great Recession. From the perspective of the estimated parameters, for the Great Moderation period of 1984-2004, Le et al. (2011) estimated the weights of the NK sector on both prices and wages to be about 0.99 and the Calvo parameters for both prices and wages to be about 0.71. However, for the period that includes the GFC, 1984-2011, Le et al. (2016a) found that the weights on the NK sector for prices and wages decreased significantly to 0.09 and 0.44, respectively. The Calvo parameter of not changing wages declined from 0.71 to 0.63, and the Calvo parameter of not changing prices increased from 0.71 to 0.97. Their findings imply that the durations of price and wage adjustments vary with the stochastic macro environment.

Motivated by this micro- and macro-level evidence, this paper investigates state-dependence at the macro-level in the open UK economy by incorporating a state-dependent price/wage contract framework into an open economy DSGE model of the UK, and estimating and testing the model on UK data using the Indirect Inference method. To the best of our knowledge, this is the first empirical study to include both state-dependent price and wage settings in an open economy DSGE model. The contribution of this paper is twofold: firstly, it provides macro-level evidence to corroborate the various micro-level evidence of state-dependence in the UK; secondly, it investigates the policy implications of a state-dependent macroeconomic model.

### 3 Model

This model section can be divided into two parts. First, we present an open economy DSGE model with fixed shares of sticky and flexprice sectors in Sections 3.1-3.7, which is the basis for the state-dependent model<sup>1</sup>. Second, we incorporate a state-dependent price/wage contract duration framework into the model in Section 3.8.

The model builds on the closed economy model of [Le et al. \(2021\)](#) and extends it to the open economy setting for the UK. Thus, the model consists of two blocks. First, a home country (UK) block building on [Le et al. \(2021\)](#), which extends the [Smets and Wouters \(2007\)](#) model by combining the NK and NC models into a hybrid model, adds the BGG banking sector, includes QE and policy regime switching – with or without the ZLB – to incorporate monetary developments following the GFC, and embeds a state-dependent price/wage setting. Second, a simple world block in the spirit of [Lyu et al. \(2023\)](#), [Gali and Monacelli \(2005\)](#), introduces exchange rates, foreign bonds, exports and imports. This implies a distinction between the CPI and the home produced goods price index. Furthermore, trade is treated as in the [Armington \(1969\)](#) model. The capital account of the balance of payments operates based on the UIP assumption between domestic and foreign bonds. It is assumed that this small open economy has a negligible effect on foreign variables; hence foreign interest rates and prices are considered as exogenous.

#### 3.1 Households

Households face two optimisation problems. First, they are expected to maximise their utility subject to budget constraints. Second, they choose between domestic and imported goods to maximise their consumption basket.

##### 3.1.1 Households' Lifetime Utility Maximisation

There is a continuum of households, indexed by  $j$ , who choose their level of consumption  $C_t(j)$ , working hours  $L_t(j)$ , foreign bonds  $B_t^f(j)$  and domestic bonds  $B_t(j)$  holdings to maximise the following utility function:

$$\max_{C_t, L_t, B_t, B_t^f} E_t \sum_{s=0}^{\infty} \beta^s \left( \frac{(C_{t+s}(j) - hC_{t+s-1})^{1-\sigma_c}}{1 - \sigma_c} \right) \exp \left( \frac{\sigma_c - 1}{1 + \sigma_l} L_{t+s}(j)^{1+\sigma_l} \right) \quad (1)$$

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1 [Lyu et al. \(2023\)](#) estimated and tested a UK DSGE model with fixed price/wage contracts and found that their model can match the behaviour of data from 1993-2016. Our work here enriches their UK model by distinguishing between domestic and CPI prices as well as between real consumer and real producer wages and, in particular, by incorporating price/wage state-dependence, to investigate whether the model can match our long sample period marked by significant economic fluctuations.

subject to the real term budget constraint

$$C_{t+s}(j) + \frac{B_{t+s}(j)}{\varepsilon_{t+s}^b (1 + R_{t+s}) P_{t+s}} + \frac{S_{t+s} B_{t+s}^f(j)}{\varepsilon_{t+s}^b (1 + R_{t+s}^f) P_{t+s}} + Tax_{t+s} \leq \frac{W_{t+s}(j) L_{t+s}(j)}{P_{t+s}} \quad (2)$$

$$+ \frac{B_{t+s-1}(j)}{P_{t+s}} + \frac{S_{t+s} B_{t+s-1}^f(j)}{P_{t+s}} + \frac{Div_{t+s}}{P_{t+s}}$$

Where  $\beta$  is the discount factor,  $h$  captures external habit formation,  $\sigma_c(\sigma_l)$  is the inverse of the intertemporal substitution elasticity between consumption (labour hours),  $P_t$  is CPI,  $S_t$  is the nominal exchange rate,  $R_t$  and  $R_t^f$  are nominal riskless rates on domestic and foreign bonds respectively. All households are assumed to face the same budget constraint in each period. At time  $t$ , each household receives a nominal wage  $W_t L_t$  by supplying labour, dividends  $Div_t$  distributed from labour unions and returns from the past position in bonds holdings. Their total income is used to consume  $C_t$ , re-invest in domestic and foreign bonds, and pay a lump sum tax  $Tax_t$ .  $\varepsilon_t^b$  is an AR(1) preference shock in financial assets, which is subject to both domestic and foreign bonds.

The households' first order conditions for  $C_t$  and  $B_t$  imply the consumption Euler equation:

$$E_t \left[ \beta \frac{(C_{t+1} - hC_t)^{-\sigma_c} \exp \left( \frac{\sigma_c - 1}{1 + \sigma_L} L_{t+1}^{1 + \sigma_L} \right)}{(C_t - hC_{t-1})^{-\sigma_c} \exp \left( \frac{\sigma_c - 1}{1 + \sigma_L} L_t^{1 + \sigma_L} \right)} (1 + R_t) \varepsilon_t^b \frac{P_t}{P_{t+1}} \right] = 1 \quad (3)$$

The first order condition for  $L_t$  gives the marginal rate of substitution between working and consumption, which is the real wage desired by the households:

$$\left( \frac{(C_t - hC_{t-1})^{1 - \sigma_c}}{1 - \sigma_c} \right) (\sigma_c - 1) L_t^{\sigma_L} \exp \left( \frac{\sigma_c - 1}{1 + \sigma_L} L_t^{1 + \sigma_L} \right) = -\lambda_t \frac{W_t}{P_t} \quad (4)$$

By combining the first order conditions for  $B_t$  and  $B_t^f$ , we obtain the Uncovered Interest Rate Parity (UIP) condition:

$$\frac{1 + R_t^f}{(1 + R_t) S_t} = \frac{1}{E_t S_{t+1}} \quad (5)$$

While some negative empirical evidence exists on the UIP condition, it is supported by recent empirical studies with data from different countries, including the UK, see [Minford et al. \(2021\)](#) and [Minford et al. \(2022\)](#). They found that UIP is generally accepted as part of a full-world DSGE model and suggested that previous evidence of UIP rejection may be attributed to bias in single-equation regression tests.

### 3.1.2 Optimal Consumption Basket

This small open economy model assumes that trade is broadly treated as in the [Armington \(1969\)](#) model. Our Armington aggregator demonstrates that there is an all-purpose home good and an all-purpose foreign good, differentiated according to their country of origin, and combined to form a consumer bundle. Notice that the Armington procedure aggregates home and foreign contributions to final consumption, which are traded, and how these are assumed to break down in detail is not detailed. Different ways of assuming how this detail are achieved are consistent with the procedure. Our Armington consumption aggregator has the form of<sup>2</sup>:

$$C_t \equiv \left[ (1 - \omega)^{\frac{1}{\sigma}} (C_t^d)^{\frac{\sigma-1}{\sigma}} + \omega^{\frac{1}{\sigma}} (\varepsilon_t^{im})^{\frac{1}{\sigma}} (C_t^{im})^{\frac{\sigma-1}{\sigma}} \right]^{\frac{\sigma}{\sigma-1}} \quad (6)$$

where  $C_t^d$  and  $C_t^{im}$  are the indices for consumption of domestically produced goods and imported goods, respectively.  $\omega$  is the weight on imported goods in the bundle, ( $0 < \omega < 1$ ).  $\varepsilon_t^{im}$  is a shock to the demand for imported goods and can be viewed as a preference error.  $\sigma$  is the elasticity of substitution between domestic and imported varieties of goods.

The CPI price index is defined as  $P_t \equiv \left[ (1 - \omega) (P_t^d)^{1-\sigma} + \omega (P_t^f)^{1-\sigma} \right]^{\frac{1}{1-\sigma}}$ , where  $P_t^d$  and  $P_t^f$  are price indices for domestically produced goods and imported goods in domestic currency, respectively. We assume that the law of one price holds, implying that  $P_t^f = S_t P_{f,t}^*$ , where  $P_{f,t}^*$  is the foreign price index of imported goods in foreign currency. Households' optimal consumption basket problem is to decide how the consumption bundle should be split between domestic and foreign varieties to maximise the Armington consumption utility subject to the expenditure constraint of  $C_t = p_t^d C_t^d + Q_t C_t^{im}$ , where  $p_t^d \equiv \frac{P_t^d}{P_t}$  is the domestic price relative to the general price level.  $Q_t$  can be seen as a unit-free measure of foreign price in domestic currency relative to the domestic general price level<sup>3</sup>. Intuitively, a rise in  $Q_t$  can be seen as a real exchange rate depreciation, as it implies a real devaluation of domestic goods and an increase in the competitiveness of domestic exports. The Armington utility maximisation problem yields the following demand functions:

$$C_t^d = (1 - \omega) (p_t^d)^{-\sigma} C_t \quad (7)$$

$$C_t^{im} = \omega (Q_t)^{-\sigma} C_t \varepsilon_t^{im} \quad (8)$$

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2 This bundle can take a variety of forms, such as differing combinations of outputs used as inputs to a final good together with home distributive service output.

3 The consumption constraint,  $P_t C_t = P_t^d C_t^d + P_t^f C_t^{im}$ , can be rewritten as  $C_t = \frac{P_t^d}{P_t} C_t^d + \frac{S_t P_{f,t}^*}{P_t} C_t^{im} \cong \frac{P_t^d}{P_t} C_t^d + \frac{S_t P_{f,t}^*}{P_t} C_t^{im} = p_t^d C_t^d + Q_t C_t^{im}$ , as  $P_t^* \cong P_{f,t}^*$  (it is assumed that exports from the UK have negligible impact on the rest of the world), where  $P_t^*$  is the general foreign price index and  $Q_t$  is the real exchange rate. This formulation of the consumption constraint is also used by [Meenagh et al. \(2010\)](#), [Dong et al. \(2019\)](#), [Minford and Meenagh \(2020\)](#) and [Lyu et al. \(2023\)](#).

Where Eq. (8) is the demand for imports,  $IM_t$ ;  $IM_t = C_t^{im} = \omega (Q_t)^{-\sigma} C_t \varepsilon_t^{im}$ . By symmetry, the demand for exports is:

$$EX_t = \omega^f (Q_t)^{\sigma^f} C_t^f \varepsilon_t^{ex} \quad (9)$$

where  $f$  is the foreign country index. Foreign consumption  $C_t^f$  is assumed to be an exogenous AR(1) process. We assume that there is no capital control; the balance of payments constraint is expressed as:

$$B_{t+1}^f - B_t^f = R_t^f B_t^f + \frac{p_t^d EX_t}{Q_t} - IM_t \quad (10)$$

### Domestic Inflation and CPI inflation

Following [Gali and Monacelli \(2005\)](#), by combining the log-linearised form of the effective terms of trade,  $tot_t = p_{f,t} - p_{d,t}$ , and the log-linearised CPI,  $p_t \equiv (1 - \omega)p_{d,t} + \omega p_{f,t}$ , a relationship between home inflation and CPI inflation can be derived as:

$$\pi_t^{cpi} = \pi_t^h + \omega \Delta tot_t \quad (11)$$

Where  $tot_t$  is terms of trade,  $\pi_t^{cpi}$  is CPI inflation and  $\pi_t^h$  is domestic inflation.

Assuming that the law of one price holds at all times, a relationship between the real exchange rate and the terms of trade can be derived, as in [Gali and Monacelli \(2005\)](#):

$$tot_t = \frac{1}{1 - \omega} q_t \quad (12)$$

By substituting Eq. (12) into Eq. (11), we obtain an expression for CPI inflation in terms of domestic inflation and the percent change in the real exchange rate, in log-linearised form:

$$\pi_t^{cpi} = \pi_t^h + \frac{\omega}{1 - \omega} \Delta q_t \quad (13)$$

This equation makes the gap between the two measures of inflation proportional to the percentage change in the real exchange rate.

The difference between CPI and the price index of domestically produced goods implies a wedge between the real consumer wage and the real producer wage; its log-linearised form is:

$$w_t^h = w_t^c + \frac{\omega}{1 - \omega} q_t \quad (14)$$

Where  $w_t^h$  is the real producer wage,  $w_t^c$  is the real consumer wage.

### 3.2 Intermediate Labour Unions – Hybrid Wage Setting

We follow [Le et al. \(2011; 2016a; 2021\)](#) in applying a hybrid wage setting, i.e., a fraction of labour markets ( $\omega_w$ ) are assumed to be imperfectly competitive with wage rigidity, similar to the NK model; whereas the remainder ( $1 - \omega_w$ ) are perfectly competitive with wage flexibility, similar to the NC model. For the NC version wage ( $W_t^{NC}$ ), it is set equal to the current expected marginal disutility of work. For the NK version, we assume that labour unions set wages according to the Calvo wage-setting rule. In each period, a fraction of labour unions ( $1 - \xi_w$ ) have the opportunity to re-adjust wages and therefore choose an optimal wage ( $W_t^\#(1)$ ), while the remaining unions ( $\xi_w$ ) cannot adjust their wages and therefore set wages with partial indexation to the CPI inflation rate in the previous period and the steady state value. The NK version of the aggregate wage index ( $W_t^{NK}$ ) is expressed as:

$$W_t = \left[ \xi_w \left[ \left( \gamma (\pi_{t-1}^{cpi})^{l_w} (\pi_*^{cpi})^{1-l_w} \right) W_{t-1}(1) \right]^{1-e_{w,t}} + (1 - \xi_w) W_t^\#(1)^{1-e_{w,t}} \right]^{\frac{1}{1-e_{w,t}}} \quad (15)$$

where  $l_w$  is the partial wage indexation coefficient.

The hybrid wage setting is assumed to be a weighted average of the corresponding NK and NC equations:

$$W_t^{\text{hybrid}} = \omega^w W_t^{NK} + (1 - \omega^w) W_t^{NC} \quad (16)$$

### 3.3 Final Goods Producers – Hybrid Price Setting

Final goods producers combine the intermediate goods sold in imperfectly competitive markets with those sold in perfectly competitive markets to produce final goods. As in [Le et al. \(2011; 2016a; 2021\)](#), it is assumed that the intermediate goods producers supply intermediate goods at prices determined partly in imperfectly competitive markets and partly in perfectly competitive markets. Therefore, the hybrid price equation is  $(P_t^d)^{\text{hybrid}} = \omega^p (P_t^d)^{NK} + (1 - \omega^p) (P_t^d)^{NC}$ , where  $\omega^p$  is the fraction of intermediate goods sold in imperfectly competitive markets,  $(P_t^d)^{NK}$  is set according to the Calvo rule and  $(P_t^d)^{NC}$  is the marginal cost. They are derived in the subsequent section.

### 3.4 Intermediate Goods Producers and Commercial Banks

We follow [Le et al. \(2016a\)](#) and incorporate a modified BGG financial friction into the model, which allows for the effects of QE. Firms purchase newly installed capital from capital producers for intermediate goods production. Capital expenditures are financed by firms' net worth and external loans from commercial banks. Therefore, firms' activities determine the production of intermediate goods, the level of capital utilisation, loan

contracts and net worth.

### 3.4.1 Production of Intermediate Goods

A representative firm uses labour and effective capital ( $K_t^s$ ) inputs to produce intermediate goods and it follows the Cobb-Douglas technology:

$$Y_t(i) = \varepsilon_t^a K_t^s(i)^\alpha [\gamma^t L_t(i)]^{1-\alpha} - \gamma^t \phi \quad (17)$$

where  $i$  is the intermediate goods sector index,  $\alpha$  is the share of capital in the production,  $\phi$  is one plus the fixed costs in production,  $\gamma^t$  is the labour-augmenting deterministic growth rate in the economy,  $\varepsilon_t^a$  is total factor productivity it is assumed to be nonstationary and follow an ARIMA (1, 1, 0) process. The firm purchases capital and chooses an optimal level of capital utilisation  $Z_t$ . Thus, the amount of effective capital is  $K_t^s(i) = Z_t(i) K_{t-1}(i)$ . The optimal capital utilisation is  $R_t^K = \psi'(Z_t)$ , where  $\psi'(Z_t)$  is the first order derivative of the adjustment cost of capital utilisation. The firm chooses the amount of effective capital and labour inputs to maximise profit. The optimal conditions give the real marginal cost and the real capital-labour ratio:

$$MC_t = \frac{(R_t^K)^\alpha \left(\frac{W_t}{P_t^d}\right)^{1-\alpha}}{\varepsilon_t^a (1-\alpha)^{1-\alpha} \alpha^\alpha} \quad (18)$$

$$K_t^s = \frac{\alpha}{1-\alpha} \frac{\left(\frac{W_t}{P_t^d}\right)}{R_t^K} L_t \quad (19)$$

Where  $\frac{W_t}{P_t^d}$  is the real producer wage.

It is assumed that a fraction of goods markets set prices flexibly as in the NC model, while the rest have sticky prices as in the NK model. In the NC version, firms set the domestic price equal to the marginal cost, Eq. (18). For the NK version, each firm is subject to nominal rigidities according to the Calvo model. In each period, a fraction of firms,  $(1 - \xi_p) \in [1, 0]$ , can choose an optimal domestic price  $[P_t^d(i)]^\#$ , while the remainder cannot re-optimize their prices and thus set prices according to the partial indexation rule,  $P_t^d(i) = (\pi_{t-1}^h)^{l_p} (\pi_*^h)^{1-l_p} P_{t-1}^d(i)$ , where  $l_p$  is the partial price indexation coefficient. Thus, the aggregate domestic price in the imperfectly competitive market evolves according to:

$$P_t^d = \left[ \xi_p \left[ (\pi_{t-1}^h)^{l_p} (\pi_*^h)^{1-l_p} P_{t-1}^d(i) \right]^{1-\varrho_{p,t}} + (1 - \xi_p) \left( [P_t^d(i)]^\# \right)^{1-\varrho_{p,t}} \right]^{\frac{1}{1-\varrho_{p,t}}} \quad (20)$$



### 3.4.2 Financial Friction and the Role of QE

In the BGG model, at time  $t$ , firms purchase newly installed capital ( $K_{t+1}$ ) from capital producers at price ( $P_t^k$ ) for production in period  $t + 1$ . In period  $t + 1$ , firms obtain revenue from the marginal product of capital ( $R_{t+1}^k$ ) and gain from selling undepreciated capital  $(1 - \delta)$  to capital producers at price  $P_{t+1}^k$ . In equilibrium, the capital arbitrage condition implies:

$$E_t(CY_{t+1}) = E_t \left[ \frac{R_{t+1}^k + (1 - \delta)P_{t+1}^k}{P_t^k} \right] \quad (21)$$

Where  $CY_{t+1}$  is the expected marginal rate of real return on capital.

Firms finance their capital purchases with net worth and external loans from commercial banks. Financial frictions evolve from information asymmetries between lenders and borrowers. The lender faces a ‘Costly State Verification’ problem and must pay a monitoring cost to observe the borrower’s realised return on capital. This cost can be viewed as the cost of bankruptcy.

In the BGG model, firms do not provide collateral. To allow for the effects of QE, we follow [Le et al. \(2016a\)](#) and extend the BGG model by assuming that banks require firms to provide a certain amount of collateral ( $c$ ) as part of their net worth. The cost of recovering this collateral is a percentage ( $\delta$ ) of its initial value;  $\delta$  corresponds to the depreciation rate in the SW07 model. We assume that firms hold cash as cheap collateral as it can be recovered directly without liquidation costs and loss of value. In times of crisis, we assume that the central bank issues cash M0 to households through QE in exchange for the bonds they hold, and households have no need for M0 and will deposit all of it with commercial banks, which then lend it to the firms to hold as collateral. Therefore, an increase in the supply of M0 will translate into a lower credit premium, resulting in a lower commercial lending rate. The model captures the impact of M0 on the credit premium through its impact on the cost of liquidating collateral ( $\delta$ ), following [Le et al. \(2016a\)](#), the log-linearized form is:

$$prem_t = E_t cy_{t+1} - (r_t - E_t \pi_{t+1}^{cpi}) = \chi (qq_t + k_t - n_t) - \vartheta m_t^0 + \varepsilon_t^{prem} \quad (22)$$

Where  $qq_t$  is the price of capital,  $n_t$  is net worth,  $\chi$  is the elasticity of the external finance premium with respect to the leverage ratio,  $\vartheta$  is the elasticity of the premium to M0 through its collateral role,  $\varepsilon_t^{prem}$  is an exogenous premium shock. This equation shows that monetary policy can affect the risk premium on bank lending to firms by adjusting the supply of M0.

### 3.4.3 Net Worth

We assume that the probability of a firm surviving to the next period is  $\theta$ , and the net worth of surviving firms carried over from the previous period is given by the past

net worth ( $\theta n_{t-1}$ ) plus total return on capital ( $cy_t$ ) minus the expected return (cost of borrowing paid to the banks):

$$n_t = \frac{K}{N} (cy_t - E_{t-1}cy_t) + E_{t-1}cy_t + \theta n_{t-1} + \varepsilon_t^{nw} \quad (23)$$

where  $\frac{K}{N}$  is the steady-state ratio of capital to net worth.

Those firms that exit the market will consume all their net worth. Thus, the consumption of these firms is equal to the probability of dying from the market ( $1 - \theta$ ) multiplied by their net worth. Its logarithmic form is:

$$c_t^e = n_t \quad (24)$$

### 3.5 Capital Producers

At the end of each period, capital producers buy existing capital  $(1 - \delta)K_{t-1}$  from intermediate goods producers and combine it with investment ( $I_t$ ) to produce new capital ( $K_t$ ). The capital producers' problem is to choose the level of investment that maximises their expected discounted profit, i.e.,  $\max_{I_t} E_t \sum_{t=0}^{\infty} \beta^t \lambda_t [P_t^k (K_t - (1 - \delta)K_{t-1}) - I_t]$  subject to the capital accumulation equation,  $K_t = (1 - \delta)K_{t-1} + \varepsilon_t^i \left[1 - S\left(\frac{I_t}{I_{t-1}}\right)\right] I_t$ , where  $\delta \in (0, 1)$  is the depreciation rate,  $S(\cdot)$  is the investment adjustment cost function as in SW07,  $\varepsilon_t^i$  is the investment-specific shock, following an AR (1) process.

### 3.6 Monetary and Fiscal Policies

#### 3.6.1 Monetary Policy

This subsection follows [Le et al. \(2016a\)](#) in presenting monetary policy separately within normal and crisis regimes, as monetary policy tools differ in crisis and non-crisis times. The monetary policy in the crisis regime incorporates new developments that have emerged since the onset of the recent GFC, including the ZLB and the implementation of QE.

**In a normal regime** (quarterly  $r_t > 0.025\%$ ), the central bank conducts conventional monetary policy according to the Taylor Rule. The supply of M0 is set to accommodate broad money M2, which is set equal to M0 plus deposits from households. Deposits are set equal to the number of loans lent to firms, which is equal to total capital expenditure minus net worth,  $deposits = borrowing = capital\ expenditure - net\ worth$ . Thus, we have  $M2 = capital\ expenditure - net\ worth + M0$ . The monetary policy frame-

work under the normal regime is summarised as follows:

$$\text{For } r_t > 0.025\% \begin{cases} r : r_t = \rho r_{t-1} + (1 - \rho) (r_p \pi_t^{cpi} + r_y y_t) + r_{\Delta y} (y_t - y_{t-1}) + \varepsilon_t^r \\ M0 : m_t^0 = m_{t-1}^0 + \vartheta_1 (m_t^2 - m_{t-1}^2) + \varepsilon_t^{m0, \text{nocrisis}} \\ M2 : m_t^2 = (1 + \nu - \mu) k_t + \mu m_t^0 - \nu n_t, \quad \nu = \frac{N}{M2}, \mu = \frac{M0}{M2} \end{cases} \quad (25)$$

Where  $\rho$  reflects the degree of interest rate smoothing.  $r_p, r_y$  and  $r_{\Delta y}$  measure the response to inflation, output and output gap, respectively.  $\nu = \frac{N}{M2}$  and  $\mu = \frac{M0}{M2}$  are the steady-state ratio of net worth to M2 and the steady-state ratio of M0 to M2 respectively.  $\vartheta_1$  is the elasticity of M0 to M2.

**In a crisis regime** (where quarterly  $r_t \leq 0.025\%$ ), the bank rate is at or below the lower bound, indicating that the conventional tool reaches its limit. Therefore, we suspend the Taylor Rule and replace it with an exogenous low bound ( $r_t = 0.025\%$ ). In addition, the central bank turns to unconventional monetary policy. QE is activated and M0 becomes the primary tool to target credit markets with the aim of reducing the risk premium on given leverage and boosting credit supply. Once the model moves away from the lower bound at some point, the Taylor Rule will be operative again. The monetary policy under the crisis regime is summarised as:

$$\text{For } r_t \leq 0.025\% \begin{cases} M0 : m_t^0 = m_{t-1}^0 + \vartheta_2 (prem_t - prem^*) + \varepsilon_t^{m0, \text{crisis}} \\ r : r = 0.025\% \end{cases} \quad (26)$$

where  $\vartheta_2$  is the elasticity of M0 with respect to premium, and  $prem^*$  is the steady-state credit premium. The mechanism works as follows: the more significant the credit spread, the more effort is required to stabilise the credit premium through M0 injection.

### 3.6.2 Fiscal Policy

The government budget constraint takes the form of  $P_t G_t + B_{t-1} = T_t + \frac{B_t}{R_t}$ . Government spending ( $G_t$ ) is exogenously determined as a time-varying component relative to the steady-state output path,  $\varepsilon_t^g = \frac{G_t}{Y \gamma^t}$ , where  $\varepsilon_t^g$  is the government spending shock affecting the amount of government spending relative to GDP, which is modelled as an  $AR(1)$  process and is also affected by productivity shocks,  $\varepsilon_t^g = \rho_g \varepsilon_{t-1}^g + \eta_t^g + \rho_{ga} \eta_t^a$ .

## 3.7 Market Clearing Conditions

The log-linearised aggregate resource constraint for the economy combined with  $\varepsilon_t^g = \frac{G_t}{Y \gamma^t}$  is given by:

$$y_t = \frac{C}{Y} c_t + \frac{I}{Y} i_t + R_*^K k_y \frac{1 - \psi}{\psi} r k_t + \frac{C^e}{Y} c_t^e + \frac{EX}{Y} ex_t - \frac{IM}{Y} im_t + \varepsilon_t^g \quad (27)$$

Where  $\frac{C}{Y}$ ,  $\frac{I}{Y}$ ,  $R_*^K k_y$ ,  $\frac{C^e}{Y}$ ,  $\frac{EX}{Y}$  and  $\frac{IM}{Y}$  are steady-state ratios.

Given that the goods markets clear and income can only be spent on goods or assets, it implies that all asset markets must also be clear. According to [Minford and Meenagh \(2020\)](#), at some terminal date  $T$ , the real exchange rate is constant, thus the change in net foreign assets is zero; the real exchange rate is constrained by the terminal conditions to ensure that the current account is balanced in the long run.

The balance of payments is subject to a constraint imposed by the transversality condition, i.e. the change in net foreign assets (the capital account) must be zero in the long-run. At the terminal date  $T$ , the equilibrium real exchange rate remains constant, the cost of servicing the current debt is covered by an equivalent trade surplus:

$$R_T^f B_T^f = - \left( \frac{p_T^d EX_T}{Q_T} - IM_T \right) \quad (28)$$

The terminal condition serves to ensure that the transversality condition is satisfied. The numerical solution path must be consistent with the constraint it imposes on the rational expectations. When solving the model, the balance of payments constraint is scaled by output, enabling the terminal condition imposes a constant ratio of net foreign assets to GDP in the long-run,  $\Delta \hat{B}_{t+1}^f = 0$  as  $t \rightarrow \infty$ , where  $\hat{B}_{t+1}^f = \frac{B_{t+1}^f}{Y_{t+1}}$ <sup>4</sup>.

### 3.8 State-dependent Price/Wage Contracts

This subsection extends the fixed price/wage contract model built in Sections 3.1-3.7 to include a state-dependent price/wage contract framework. The fixed-duration model assumes that a fixed fraction of goods markets are imperfectly competitive with nominal rigidities, while the rest are perfectly competitive with flexible pricing; the labour market is similar. To embed state-dependent variation, we assume that the fraction of firms with flexible prices and the fraction of unions with flexible wages are state-dependent rather than fixed, and are based on an increasing function of past inflation.

We define the sticky price/wage sectors (or NK sectors) as the long duration sectors because prices/wages are sticky for more than one quarter. On the other hand, the flexible price/wage sectors (or NC sectors) are defined as the short duration sectors because prices/wages constantly change every quarter. In the fixed price/wage duration model,

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<sup>4</sup> The model is solved under rational expectations using the projection method outlined by [Fair and Taylor \(1980\)](#) and [Minford et al. \(1984; 1986\)](#). At the terminal date  $T$ , the expectations must meet the terminal conditions of the model. These conditions are imposed to guarantee that the simulated paths of the endogenous variables converge to long-term levels at the terminal date, in line with the long-run implications of the model ([Minford et al., 1979](#)). Imposing the terminal conditions on the expectations involves solving the equilibrium system sometime in the future, given that shocks have stopped, the stationary variables have reached their long-run constant values, and the trended variables have maintained a constant growth rate. Additionally, the transversality condition must hold to ensure that the net foreign assets are stable and that net international debt does not grow over time.

the long duration sectors have fixed weights, i.e.,  $\omega^w$  and  $\omega^p$  are fixed. As a result, the short duration sectors also have fixed weights:  $(1 - \omega^w)$  and  $(1 - \omega^p)$  are fixed. Furthermore, firms/labour unions change their prices/wages according to the fixed Calvo probabilities. To incorporate state-dependence, we relax the assumption of fixed durations and assume that the structure of the price/wage durations is state-dependent. This implies that firms and labour unions adjust their prices and wages more frequently in response to aggregate shocks and therefore some of them shift from long duration to short duration in this state-dependent model.

We assume that firms' decisions to change their prices depend on the shocks' size. If the shock size is less than the critical shock size, at which the cost of changing prices is equal to the gain from providing insurance to customers, then the choice would be to stabilise prices to ensure customers against uncertainty. However, if the shock size exceeds the critical value, it would then be optimal to update prices and reset them optimally to respond to the shock, as the cost of providing this insurance to customers in this case is greater than the expected benefit. In other words, firms will only adjust prices when the shock is greater than the critical shock size. The wage adjustment framework is similar.

It is assumed that the variance of the idiosyncratic cost-shock distribution used by price setters is state-dependent. More specifically, we assume that it is associated with the size of recent inflation shocks, represented by  $\Pi$  and measured by a moving average of inflation. Therefore, recent inflation shocks to the economy,  $\Pi$ , affect the variance of the cost-shock distribution, which in turn affects the Calvo probability of not changing prices. For example, if there is an increase in recent inflation, it would cause a higher variance of the idiosyncratic cost-shock distribution. The higher variance indicates that the critical shock level occurs at a lower percentile of the distribution, as shown in [Figure 1](#). A lower percentile means a lower Calvo probability of not changing prices. Hence, the recent inflation affects the variance of idiosyncratic shock distribution, thereby changing the Calvo probability. Wage changes are similar.

If recent inflation rises, the Calvo probability of not changing prices consequently decreases, causing more sectors to become flexprice, which may subsequently decrease the Calvo parameters in the remaining sectors (i.e. sticky-price sectors). We describe this as a 'reduction effect' on the Calvo parameters in the remaining sectors. On the other hand, there is an 'abandonment effect', as the sectors closer to the short duration sector would shift to it, leaving those sectors with higher Calvo parameters in the sticky sector. This abandonment effect is contrary to the reduction effect. Therefore, the Calvo parameters for the NK sectors may increase, decrease, or remain the same. We estimate the Calvo parameters and other model parameters using the Indirect Inference method, but allowing for this net response to  $\Pi$ .

We use the function proposed by [Le et al. \(2021\)](#) to relate the price/wage parameters to the variance of past inflation:

$$\omega^i = \exp(-\vartheta^i \Pi) \quad (29)$$

where  $i = p, w$ , and  $\Pi$  is the square of the moving average of inflation over the past four years.  $\omega^p$  and  $\omega^w$  are proportions of sticky prices and wages, respectively.  $\vartheta^p$  and  $\vartheta^w$  are parameter responses of NK weights to the variance of inflation for prices and wages, respectively.  $\vartheta^p$  and  $\vartheta^w$  are determined empirically through the Indirect Inference estimation. The weights on the long duration sectors,  $\omega^i$ , are calculated according to Eq. (29); thus, the weights now are state-dependent. This state-dependence is added to the DSGE model. The model is nonlinear as the price/wage parameters change endogenously with inflation shocks.

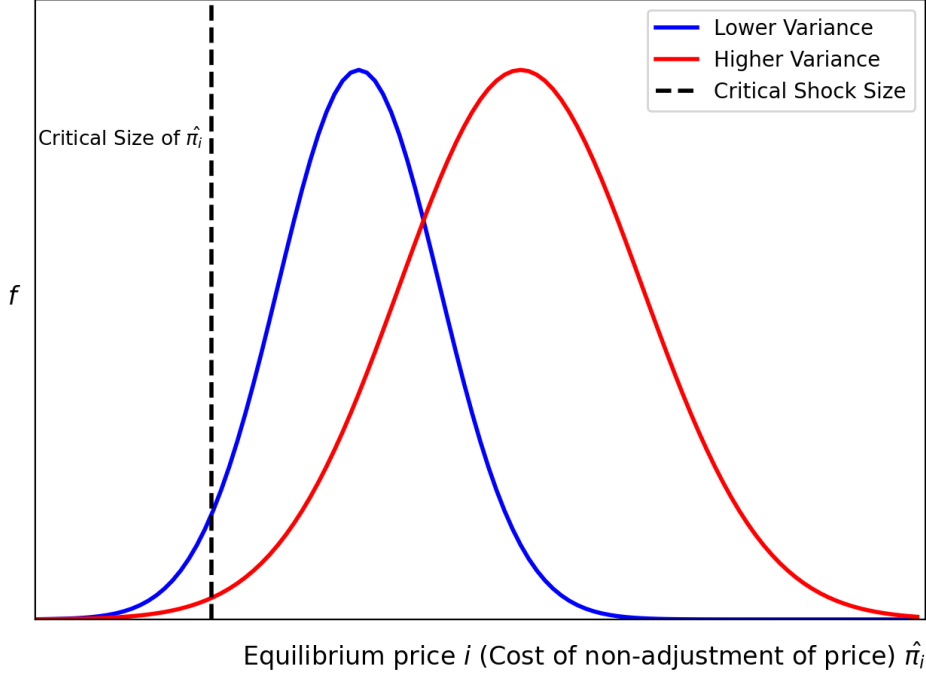


Figure 1: Distribution of Idiosyncratic Shocks

## 4 Estimation Method

### 4.1 The Method of Indirect Inference

The model is estimated and tested using a simulation-based Indirect Inference method, which was first introduced by [Smith \(1993\)](#), further developed by [Minford et al. \(2009\)](#) and [Le et al. \(2011\)](#) using Monto Carlo experiments, and extended to test nonstationary

data by [Meenagh et al. \(2012\)](#)<sup>5</sup>. Indirect means choosing an auxiliary model (e.g. VAR, VARX or VARMA) that is independent of the theoretical model as the lens to generate a description of the data. This is then used to indirectly assess how well the theoretical model performs. This description of the data can be summarised by the estimated parameters of the auxiliary model. Through the Indirect Inference method, models of any size, complexity and non-linearity can be estimated and tested by comparing the performance of the auxiliary model estimated on simulated data with the performance of the auxiliary model estimated on observed data.

Regarding the choice of the auxiliary model, we follow [Meenagh et al. \(2012\)](#) and use a VARX to represent our log-linearised model as we have nonstationary data and residuals. The comparison uses a statistical criterion based on a Wald test, which measures the difference between the vector of relevant VARX parameters from simulated and actual data. A correct structural model should generate sensible simulated data and corresponding VARX estimates that are not significantly different from the actual data and their corresponding VARX estimates. Our Wald test is based on three variables because of the ‘ideal power’ – not so high as to stop a good model from passing, but high enough to reject bad models with high probability. [Meenagh et al. \(2019\)](#) show that using a VAR with three variables (it does not matter which three are chosen) is adequate to provide an indirect test with high power for a large model. However, adding more variables would produce excessive power. A VARX (1) containing our three variables of interest is the basis of the Wald test, which takes the form of:

$$\begin{bmatrix} y_t \\ \pi_t \\ r_t \end{bmatrix} = B \begin{bmatrix} y_{t-1} \\ \pi_{t-1} \\ r_{t-1} \end{bmatrix} + C \begin{bmatrix} T \\ \varepsilon_t^a \\ b_{t-1}^f \end{bmatrix} + \begin{bmatrix} \epsilon_t^y \\ \epsilon_t^\pi \\ \epsilon_t^r \end{bmatrix} \quad \text{where } B = \begin{bmatrix} \theta_{yy} & \theta_{y\pi} & \theta_{yr} \\ \theta_{\pi y} & \theta_{\pi\pi} & \theta_{\pi r} \\ \theta_{ry} & \theta_{r\pi} & \theta_{rr} \end{bmatrix}$$

Where  $T, \varepsilon_t^a$  and  $b_{t-1}^f$  are the deterministic time trend, the nonstationary residuals and lagged nonstationary foreign assets, respectively.

When testing the model, we simulate the structural model and apply the auxiliary model to each simulated dataset. This gives us a distribution of the auxiliary model parameters. We then compute the Wald statistic to see if the estimates of the auxiliary model obtained from the actual data fall within some confidence interval suggested by this distribution. The Wald statistic is defined as  $W = (\beta^\alpha - \bar{\beta}^s)' \Omega^{-1} (\beta^\alpha - \bar{\beta}^s)$ .  $\beta$  contains nine coefficients from the matrix  $B$  describing the dynamic properties of

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<sup>5</sup> The reasons for using Indirect Inference rather than the popular Bayesian method are as follows. First, the Bayesian method heavily relies on prior information about the macroeconomy and assumes that both the prior distribution and the model structure are correct. However, the prior information is usually not fully informed. Consequently, the risk of biased results could arise from wrong prior choices. Second, we aim to estimate and test a non-linear model on nonstationary data. Third, Indirect Inference has been proven to be a powerful method for testing structural macro models; see [Minford et al. \(2009\)](#), [Le et al. \(2010\)](#), [Le et al. \(2015\)](#), [Le et al. \(2016b\)](#) and [Meenagh et al. \(2019\)](#).



the model and data, plus the three error variances measuring the size of variation. Thus,  $\beta = \begin{bmatrix} \theta_{yy} & \theta_{y\pi} & \theta_{yr} & \theta_{\pi y} & \theta_{\pi\pi} & \theta_{\pi r} & \theta_{ry} & \theta_{r\pi} & \theta_{rr} & \text{var}(\epsilon_t^y) & \text{var}(\epsilon_t^\pi) & \text{var}(\epsilon_t^r) \end{bmatrix}'$ .  $\Omega = \text{cov}(\beta^\alpha - \bar{\beta}^s)$ .  $\beta^\alpha$  is the VARX parameters estimated on actual data, and  $\bar{\beta}^s$  is the average of VARX parameters obtained from 1000 sets of bootstrapped simulations. We do not reject the null hypothesis that the model is the true model only if it can jointly match the 12 coefficients in  $\beta$ . A summary of the steps to implement the Indirect Inference Wald test by bootstrapping can be found in [Meenagh et al. \(2012\)](#).

The optimal parameter set for the structural model is the one that minimises the distance between the VARX estimates based on simulated data and those based on the actual data, as indicated by the minimum Wald statistic - or the minimum t-statistic<sup>6</sup>. To search for the optimal parameter set, we use the Simulated Annealing algorithm, in which a search is conducted over a wide range around initial values by random jumps.

## 4.2 Data

The model was estimated and tested on unfiltered quarterly UK data for 1955Q1-2021Q1<sup>7</sup>. From October 1949 to May 1972, the UK had a fixed exchange rate regime (or the Bretton Woods system) in which the BoE intervened in the currency market to keep the exchange rate close to the fixed exchange rate target to maintain economic stability. This regime poses a problem for our estimation over the entire sample period of 1955-2021. We address this by adding an exchange rate target to the Taylor Rule ([Taylor, 1995](#)) for the period 1955Q1-1972Q2 and turning it into a standard Taylor Rule for the period 1972Q3-2021Q1.

According to [Giavazzi and Giovannini \(1989\)](#), a permanent fixed exchange rate regime differs from a regime where a monetary authority pegs its currency to a numeraire but is free to correct its exchange rate. For the pre-1972 period, under the Bretton Wood system of a fixed-but-adjustable exchange rate, the model treats it as floating with the version of the Taylor Rule with a real exchange rate target included. In other words, the pre-1972 model assumes that a ‘fixed’ rate is treated as adjustable whenever an adjustment is needed under the Bretton Woods system. [Clarida et al. \(1998\)](#) included the real exchange rate and its target in the Taylor Rules for Italy, France and the UK for the ERM period. Since both the ERM and Bretton Woods system aimed to maintain a fixed-but-adjustable exchange rate regime, we follow them in adding an exchange rate

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6 The Wald statistic is converted into a normalised t-statistic using  $t\_statistic = \left( \frac{\sqrt{2W} - \sqrt{2k-1}}{\sqrt{2W_i^{0.95}} - \sqrt{2k-1}} \right) \times 1.645$ , where  $k$  represents the number of parameters in  $\beta$ ,  $W$  and  $W_i^{0.95}$  are Wald statistics for the actual data and 95<sup>th</sup> percentile of the simulated data, respectively.

7 The use of filtered data may eliminate or distort the dynamic properties of the model in ways that are not easily detected. Therefore, we use the original data and retain the stochastic trends in the model, as one of our interests is to observe how the behaviour of the stochastic trend is transferred through the model.

target to the Taylor Rule; see [Engel and West \(2004\)](#), and [Wang and Wu \(2009\)](#) for more examples.

For the post-1972 period, we combine the 1972-1992 floating exchange rate regime and the inflation targeting period 1992-2021, using the standard Taylor Rule without the exchange rate over the whole period. Although the UK is a small open economy, other empirical studies for the UK, including [Lyu et al. \(2023\)](#) using data from 1993-2016 and [Le et al. \(2023b\)](#) using data from 1986-2016, demonstrate that the Taylor Rule without the exchange rate also performs well in terms of data fit. During the earlier 1972-1992 floating period monetary policy was guided solely by domestic considerations, which argues in favour of omitting the exchange rate element; in terms of responses to the domestic elements, the Taylor Rule formulation should be a reasonable approximation to UK policy, much as [Taylor \(1995\)](#) argued it well represented US monetary policy under its floating regime. Hence for the post-1972 period, we do not include the exchange rate in the Taylor Rule - with, as it turns out, successful empirical results.

## 5 Empirical Results

Using Indirect Inference estimation, we found that the state-dependent DSGE model can match the dynamic behaviour of the UK data very well over the sample period 1955-2021, with a p-value of 0.087 (see [Table 1](#)). It is worth noting that our sample period encompasses a turbulent economic environment, particularly the stagflation of the 1970s. This Great Inflation environment poses a challenge for models with fixed price/wage durations to fit the data. For example, [Le et al. \(2011\)](#) found that their fixed-duration model failed to fit the behaviour of the US data for 1947-1984 using Indirect Inference. However, in their subsequent work ([Le et al., 2021](#)), by introducing state-dependence into the model, they succeeded in explaining the data behaviour over the long sample period 1959-2017. Our results reinforce their findings on state-dependence at the macro-level, and show that the state-dependent DSGE model is effective in capturing the dynamic behaviour of key macroeconomic variables in the UK for 1955-2021.

The parameter estimates are reported in [Table 1](#). Most of the estimates are close to those of [Lyu et al. \(2023\)](#) for the UK economy and [Le et al. \(2016a; 2021\)](#) for the US economy. Although a few estimates exhibit significant differences from theirs, these are not far from those in the literature as the search range is chosen in line with previous literature.

[Figures 2 and 3](#) show actual inflation data, the square of MA inflation and its corresponding state-dependent NK price/wage weights. As shown, the NK weights on prices and wages are affected by the state of the economy (inflation); the higher the inflation, the lower the NK weights. For example, in the 1970s, the NK weights fell significantly as inflation increased sharply, then rose to near one during the Great Moderation. [Figure 4](#)

provides examples of simulations (shown in red) that tend to match the features of the movements in the actual data (shown in blue), hence accounting for the good p-value. The last row of the figure shows the corresponding time-varying NK price/wage weights in these simulations, which change endogenously with inflation.

Table 2 shows the auxiliary model estimates on the actual data and the 95% confidence bounds from the simulations. We found that only one of the nine parameters lies outside the bounds, i.e., the model under-predicts the response of output to lagged output by a small margin. The data for interest rate variance and output variance are slightly below the model's 95% confidence bounds. However, the model fits overall, as indicated by the P-value of 0.087.

Table 1: Parameter Estimates

Symbol	Description	Estimates
Households' parameters		
$\sigma_c$	Intertemporal elasticity of substitution	1.6408
$h$	External habit formation	0.7016
$\xi_w$	Elasticity of labour supply	2.8257
Firms' parameters		
$\varphi$	Elasticity of capital adjustment	4.4871
$\psi$	Elasticity of capital utilization	0.9485
$\phi$	1+share of fixed costs in production	1.8837
$\alpha$	Share of capital in production	0.5765
The Taylor Rule parameters		
$r_p$	Taylor Rule response to inflation	3.1879
$\rho$	Interest rate smoothing	0.5769
$r_y$	Taylor Rule response to output	0.0172
$r_{\Delta y}$	Taylor Rule response to change in output	0.0463
$r_q$	Taylor Rule response to deviation from real exchange rate target	0.0445
Financial frictions and money response parameters		
$\chi$	Elasticity of the premium with respect to leverage	0.1048
$\vartheta$	Elasticity of the premium to M0	0.0413
$\vartheta_1$	Money response to credit growth	0.0692
$\vartheta_2$	Money response to premium	0.0700
Price and wage setting parameters		
$\xi_w$	Probability of not changing wages	0.6101
$\xi_p$	Probability of not changing prices	0.5462
$l_w$	Wage indexation	0.3965
$l_p$	Price indexation	0.0554
$\vartheta^w$	Parameter response of NK weight - wages	105.3684 <sup>a</sup>
$\vartheta^p$	Parameter response of NK weight - prices	93.5372 <sup>a</sup>
$\omega^w$	Proportion of sticky wages	state-dependent
$\omega^p$	Proportion of sticky prices	state-dependent
Wald ( $Y, \pi, R$ )		18.3008
P-value		0.0870
Transformed T-statistic		1.0455

<sup>a</sup> It should be noted that [Le et al. \(2021\)](#) transformed their dataset into percentages by multiplying each value by 100, whereas our dataset is not expressed in percentage terms. Therefore, when employing Le et al.'s non-linear function  $\omega^i = \exp(-\vartheta^i \Pi)$  to our dataset, we use large  $\vartheta^p$  and  $\vartheta^w$  values to ensure that our time-varying NK weights are broadly in line with theirs.

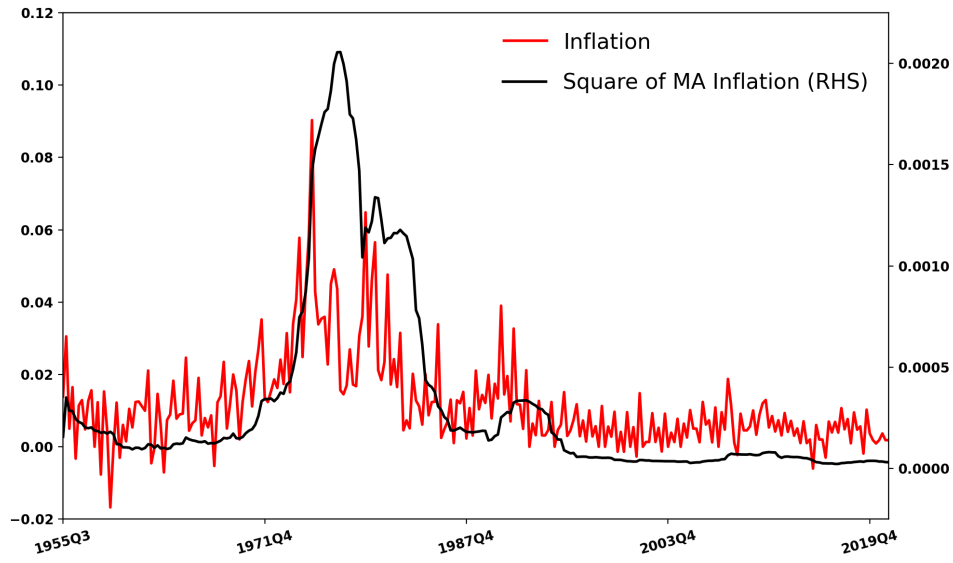


Figure 2: Inflation and the Square of MA Inflation

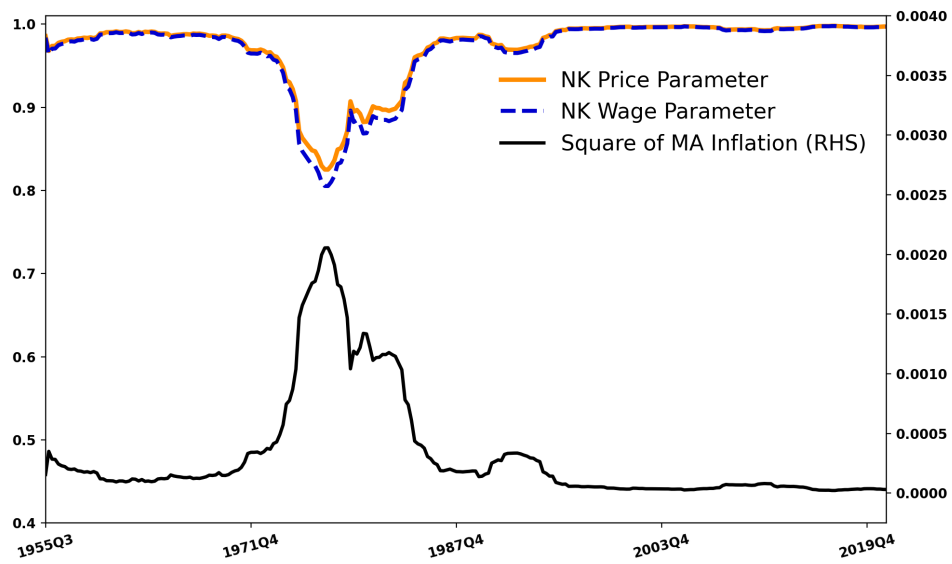


Figure 3: Time Varying NK weights

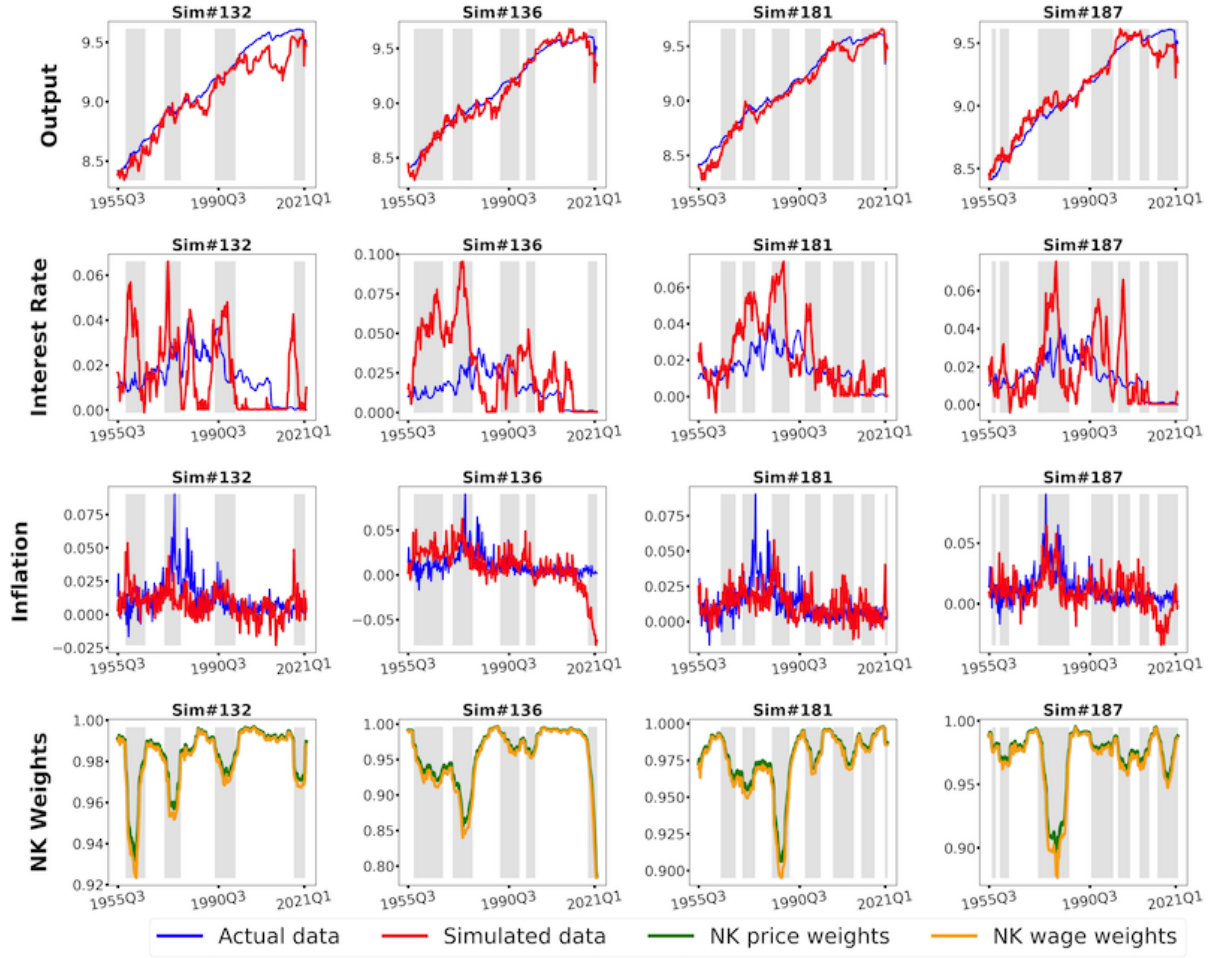


Figure 4: A Selection of Simulations

Note: First, shaded areas show significant drops in the NK weights induced by notable inflation variance; in non-ZLB scenarios, interest rates respond to inflation fluctuations via the Taylor Rule. Second, our simulations for the 1955-1972 period do not include ZLB regime switches because the actual data during this time do not suffer from any ZLB issues. This explains the occasional negative interest rates in simulations prior to 1972, e.g. in Simulation#181.

Table 2: Auxiliary Model Parameter Bounds

	Actual	2.5 <sup>th</sup> Percentile	97.5 <sup>th</sup> Percentile	In/Out
$\theta_{yy}$	0.9817	0.7663	0.9493	Out
$\theta_{y\pi}$	-0.0712	-0.2964	0.4465	In
$\theta_{yr}$	0.1644	-0.5485	0.1798	In
$\theta_{\pi y}$	-0.0019	-0.0149	0.0482	In
$\theta_{\pi\pi}$	0.3572	0.0815	0.8136	In
$\theta_{\pi r}$	0.1672	-0.2273	0.2336	In
$\theta_{ry}$	0.0030	-0.0107	0.0495	In
$\theta_{r\pi}$	0.0008	-0.1596	0.0390	In
$\theta_{rr}$	0.8936	0.8314	0.9999	In
$\text{var}(\epsilon^y)$	0.000409	0.000578	0.001037	Out
$\text{var}(\epsilon^\pi)$	0.000093	0.000061	0.000177	In
$\text{var}(\epsilon^r)$	4.40e-06	8.39e-06	0.000092	Out

## 5.1 Impulse Responses

This section examines the impulse responses of variables to structural shocks under the NK model and the flexprice (FP) model. For the entirely NK model, we set the NK weights to one with corresponding Calvo parameters; for the FP model, the NK weights are set to zero.

### 5.1.1 Responses to Taylor Rule Shock

Figure 5 shows the IRFs to a positive Taylor Rule (contractionary monetary policy) shock, which is a pure demand shock. The output response is more pronounced, but the inflation response is weaker under the NK model than in the FP model. The explanation for this difference is that under the NK model, a pure demand shock affects output directly; however, due to price rigidity, inflation does not respond much in the short run and only responds substantially to the resulting output gaps in the medium run. In the FP model (with flexible prices), the shock disturbs prices as they vary with changes in marginal costs and the output gap; however, the impact of the shock on output is limited as inflation responds quickly to stabilise output. Thus, in response to the demand disturbance, the NK model destabilises output but stabilises inflation through the Calvo framework, while the FP model stabilises output via flexible price adjustments. Overall, the FP model implies a rapid price response and a smaller real effect of monetary shocks than the NK model; output, consumption and labour exhibit smaller and less persistent responses, as shown in the figure.

The sign of the impulse response is fully consistent under both NK and NC models. A rise in the nominal interest rate hits consumption, investment, output, labour hours, real consumer wages and inflation negatively. In the financial sector, the shock decreases firms' net worth, which raises the external finance premium and further reduces investment. The decline in net worth leads to an increase in distressed borrowing, thereby resulting in a rise in M0. In the foreign sector, deflation and higher nominal interest rates (implying higher real interest rates) decrease the real exchange rate. Thus, the appreciation of sterling induces imports and lowers exports as domestic prices are relatively higher than foreign prices. The net foreign bond position decreases as net exports decrease.

### 5.1.2 Responses to Government Spending Shock

Figure 6 captures the effects of a rise in government spending. Under the NK model with price rigidity, the positive demand effects of the fiscal shock have a low impact on prices, and as a result do not transmit into higher inflation. However, it creates output turbulence. Conversely, under the FP model with flexible prices, the positive demand effects cause an increase in the output gap, which is transmitted into higher inflation. Therefore, the NK model has a more significant output response but a smaller inflation



response than the FP model.

In both versions of the model, the increase in aggregate demand drives up output, labour hours, real wages, and inflation. Interest rates rise via the responses of the Taylor Rule, which reduces investment and capital. Regarding consumption, in the NK model, consumption increases with expected income. In contrast, in the FP model with perfect information, government spending is seen as a negative wealth shock to households, as households recognise that taxes must be increased either now or in the future to pay for it. The negative wealth effect causes a decline in consumption and an increase in hours worked. In the foreign sector, the real exchange rate falls, and the domestic currency appreciates. Thus, exports decrease, and imports increase because domestic products are less competitive than foreign ones. The lower net export lowers net foreign asset accumulation.

Overall, the behaviour generated by our state-dependent model is in line with that presented in [Le et al. \(2021\)](#) and micro-level studies. Specifically, it indicates that prices change more frequently during periods of high inflation. Thus, high inflation periods are closer to the scenario described in the FP model, i.e., prices respond to shocks more quickly and exhibit less persistence. Moreover, the real effect of monetary shocks is smaller.

## 5.2 Variance Decomposition

We perform a variance decomposition analysis to examine how the model responds to shocks for both short-run (1 year) and long-run (5 years) time scales. [Tables 3 and 4](#) show the analysis for the pre-1972 and post-1972 periods, respectively<sup>8</sup>. The shock processes involved are detailed in Appendix B. We treat all except productivity as stationary or trend-stationary AR processes; productivity we treat as nonstationary, since productivity growth is the result of innovations. The appendix details various tests of these assumptions on the residual series. Ultimately it is the overall model Wald test that judges them.

As shown, output fluctuations in the short run are dominated by the net trade shock, which is consistent with the finding in [Le et al. \(2023a\)](#). Additionally, in the short run, a significant proportion of output fluctuations is attributed to demand shocks, especially the net trade shock, the investment shock and the Taylor Rule shock. This result is in line with the high estimated weights on the NK sectors. In the long-run, the productivity shock plays an important role in explaining output fluctuations, in line with the findings in [Le et al. \(2021\)](#) for the US. This comes about because productivity is non-stationary so that its shock has a permanent effect on the level. The nominal interest rate is heavily

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<sup>8</sup> To reiterate, for the pre-1972 period, the model's Taylor Rule equation has an exchange rate target included.

affected by the Taylor Rule shock and the price mark-up shock in the short run, and the productivity shock in the long-run. Inflation variation is primarily explained by the price mark-up shock, followed by the Taylor Rule and productivity shocks.

The productivity shock also contributes substantially to the volatility of investment, wages, consumption, working hours and imports, especially in the long-run as productivity shocks are permanent, again consistent with [Le et al. \(2021\)](#) for the US. The results from the post-1972 model exhibit strong similarities to those from the pre-1972 model.

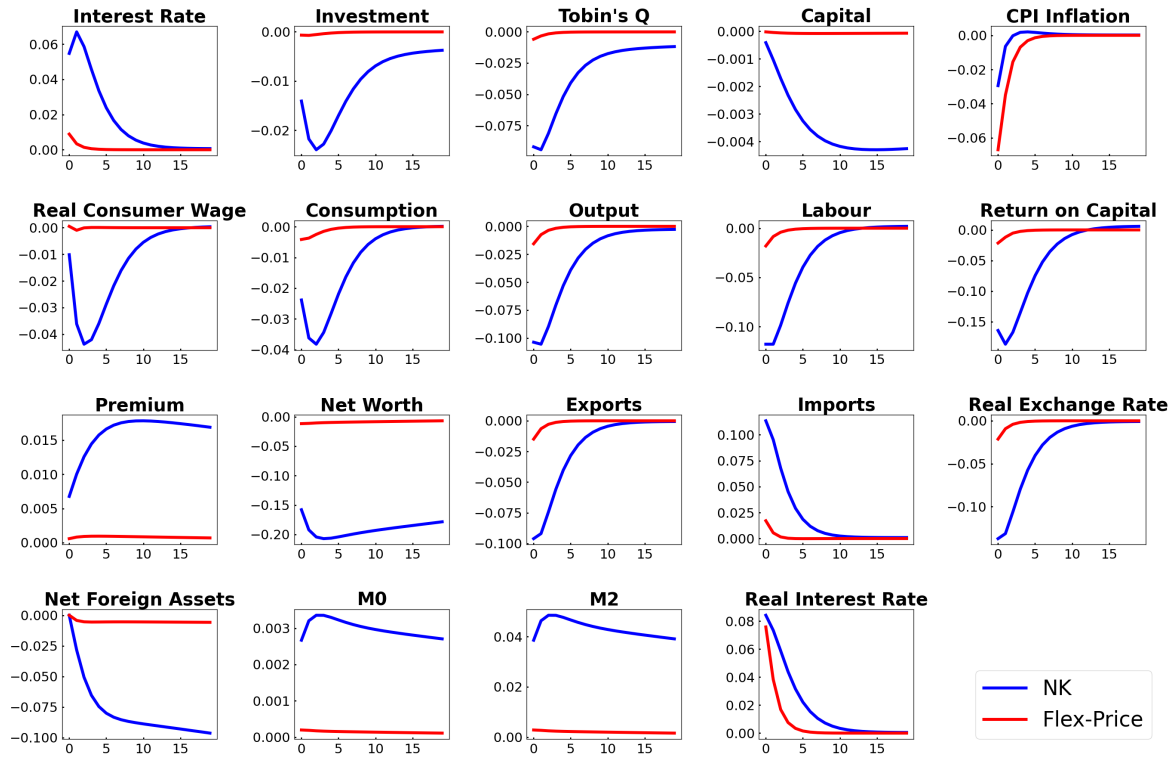


Figure 5: IRFs to a Positive Taylor Rule Shock

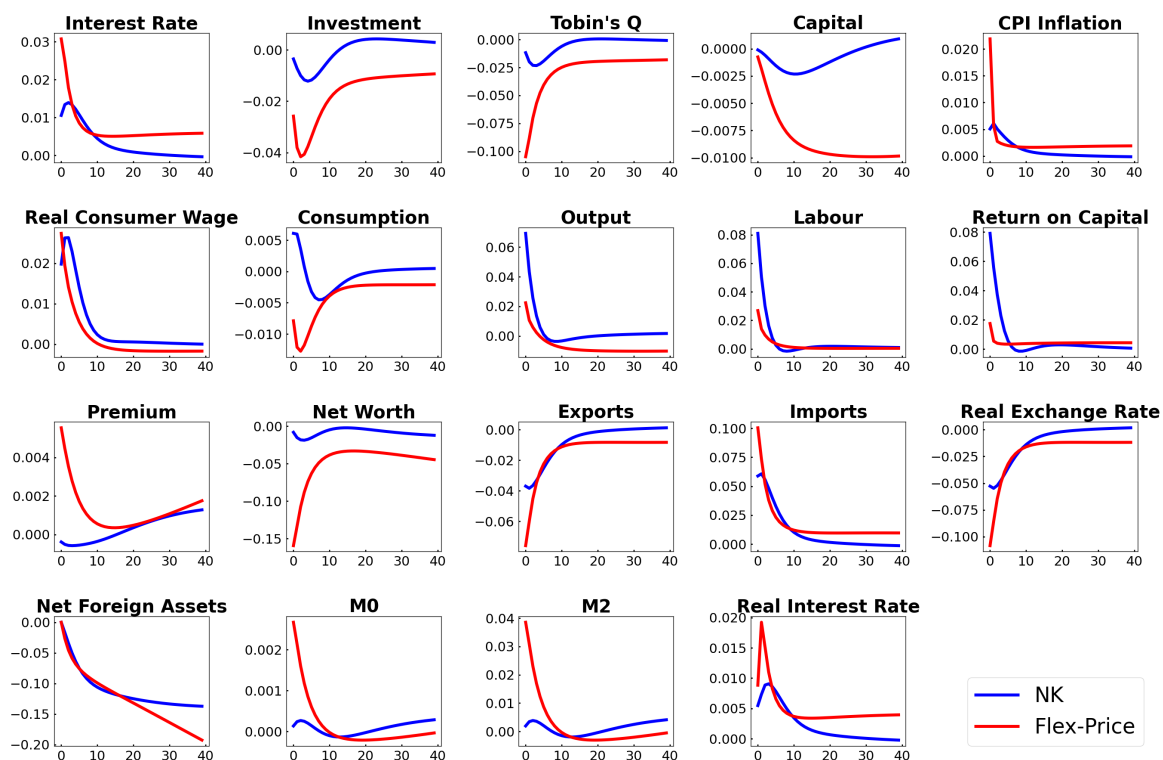


Figure 6: IRFs to a Positive Government Spending Shock

Table 3: Variance Decompositions - Pre-1972 Model

Shock	Interest Rate	Investment	Inflation	Wage	Consumption	Output	Hours	Exports	Imports	Exchange Rate
<b>Short-run (1 year)</b>										
Government Spending	1.8471	0.0527	2.0440	6.2473	0.2925	5.1139	1.6375	0.7566	3.9982	14.4187
Consumer Preference	0.0145	0.0056	0.0153	0.2374	14.2587	0.1134	0.0343	0.0025	1.7541	0.0482
Investment	0.5940	82.5751	1.0274	1.3144	1.1141	12.4884	3.3560	0.0613	0.4465	1.1687
Taylor Rule	54.5222	0.0035	14.5679	1.4366	7.9128	10.9079	3.3378	2.3340	5.5234	44.4819
Productivity	3.9240	16.6347	6.1271	30.5997	64.8986	6.7473	69.1611	1.1341	39.0954	2.4807
Price Mark-up	33.0149	0.0019	70.5412	9.0269	4.2590	6.2506	1.7905	1.3040	3.1919	24.8525
Wage Mark-up	0.4264	0.0928	0.6594	25.8835	0.6255	0.7210	0.3063	0.1386	0.3053	2.6411
Labour Supply	0.0744	0.0239	0.1147	2.8926	0.0954	0.1612	0.0628	0.0295	0.0727	0.5630
Premium	0.0003	0.0297	0.0001	0.0011	0.0011	0.0112	0.0027	0.0000	0.0003	0.0002
Net Worth	0.0829	0.5758	0.0601	0.3542	0.1553	1.6153	0.4716	0.0054	0.0803	0.1025
M0	0.0000	0.0035	0.0000	0.0001	0.0001	0.0009	0.0002	0.0000	0.0000	0.0000
Export	4.3364	0.0004	3.8071	17.4066	5.0281	43.0840	15.7772	94.1280	4.1209	7.2230
Import	1.1630	0.0005	1.0357	4.5995	1.3588	12.7848	4.0621	0.1060	41.4110	2.0196
<b>Long-run (5 years)</b>										
Government Spending	1.9235	0.1054	1.8881	1.9371	0.2571	4.3554	0.5900	0.8039	3.3287	13.9481
Consumer Preference	0.0153	0.0146	0.0161	0.0589	5.3582	0.1032	0.0127	0.0032	1.0679	0.0547
Investment	5.7817	26.5597	4.7961	3.2558	4.2096	5.4337	9.5888	0.2701	3.5395	4.6855
Taylor Rule	35.8297	0.0029	10.1758	0.6463	4.0892	10.8545	1.3975	1.8033	3.6204	31.2879
Productivity	30.1039	71.1890	29.3617	76.5496	80.5971	22.1032	79.1282	20.1838	55.0347	20.5744
Price Mark-up	19.6117	0.0013	47.9286	2.2982	1.8676	5.5981	0.6801	0.9196	1.9660	15.9561
Wage Mark-up	0.3812	0.2020	0.5231	6.3777	0.4414	0.9740	0.1409	0.1248	0.2334	2.1654
Labour Supply	0.1157	0.0856	0.1277	0.8570	0.1139	0.3240	0.0394	0.0383	0.0756	0.6643
Premium	0.0017	0.0572	0.0016	0.0009	0.0014	0.0685	0.0029	0.0001	0.0010	0.0013
Net Worth	0.1803	1.7106	0.1243	0.2595	0.1385	5.8787	0.3369	0.0133	0.1467	0.2302
M0	0.0019	0.0579	0.0022	0.0004	0.0003	0.0393	0.0011	0.0001	0.0008	0.0020
Export	4.9545	0.0074	4.1030	6.3125	2.3507	32.7650	6.5337	75.7257	4.0128	8.4541
Import	1.0989	0.0063	0.9518	1.4460	0.5752	11.5025	1.5478	0.1139	26.9726	1.9762

Note: Values in the table are expressed in per cents. The deeper the shading is, the more significant the contribution.

Table 4: Variance Decompositions - Post-1972 Model

Shock	Interest Rate	Investment	Inflation	Wage	Consumption	Output	Hours	Exports	Imports	Exchange Rate
<b>Short-run (1 year)</b>										
Government Spending	1.5721	0.0938	2.0675	2.2768	0.1343	2.2420	1.1728	0.5244	2.5622	12.9310
Consumer Preference	0.0481	0.0032	0.0578	0.3349	34.7796	0.2395	0.1166	0.0042	2.9547	0.1030
Investment	0.4632	37.6387	0.9285	0.4446	0.6537	6.0194	2.6073	0.0252	0.1815	0.6202
Taylor Rule	63.4654	0.0023	19.6530	0.7254	6.9309	7.8489	3.8709	1.4292	3.3509	35.2394
Productivity	5.6690	61.0130	9.5156	43.4846	38.2521	16.2945	57.4493	43.1622	37.2581	2.4392
Price Mark-up	23.4126	0.2149	61.7214	8.4583	8.2600	9.4030	4.2980	1.4376	3.3279	35.4481
Wage Mark-up	0.8395	0.5076	1.6485	26.9563	2.2499	1.9646	1.2157	0.2602	0.5153	6.4156
Labour Supply	0.5960	0.1144	1.0901	10.1241	0.7819	1.0542	0.6449	0.1694	0.4157	4.1763
Premium	0.0017	0.1149	0.0009	0.0032	0.0042	0.0393	0.0149	0.0000	0.0009	0.0010
Net Worth	0.0717	0.2911	0.0603	0.1329	0.1011	0.8636	0.4063	0.0024	0.0362	0.0603
M0	0.0001	0.0059	0.0000	0.0002	0.0002	0.0019	0.0007	0.0000	0.0000	0.0001
Export	2.3092	0.0001	1.8600	4.2818	5.1835	35.3251	18.5753	52.9385	1.2563	1.4152
Import	1.5516	0.0001	1.3963	2.7769	2.6685	18.7039	9.6271	0.0467	48.1402	1.1506
<b>Long-run (5 years)</b>										
Government Spending	1.0979	0.1602	1.2280	0.4181	0.1541	1.7352	0.3781	0.5770	1.5715	9.6216
Consumer Preference	0.0232	0.0059	0.0285	0.0498	7.7181	0.1781	0.0371	0.0038	1.3575	0.0633
Investment	10.3340	19.2371	9.8482	1.6289	0.4254	6.2685	5.1089	0.8598	3.1233	14.3377
Taylor Rule	27.6180	0.0018	8.7631	0.1988	2.1159	6.8214	1.4327	1.1763	1.6637	19.6141
Productivity	45.8053	78.1086	47.9000	87.9928	82.0422	23.2591	74.6539	13.8187	64.1677	25.4604
Price Mark-up	9.1860	0.1840	26.7676	1.4142	2.2393	7.5098	1.4457	1.0770	1.5367	17.9594
Wage Mark-up	0.7407	0.8573	1.0835	4.0338	1.0141	2.8436	0.4675	0.3359	0.4648	5.6014
Labour Supply	0.5850	0.3386	0.7389	1.8162	0.5496	1.7011	0.3381	0.2156	0.2895	3.5947
Premium	0.0120	0.2278	0.0126	0.0021	0.0041	0.2080	0.0197	0.0005	0.0038	0.0083
Net Worth	0.1033	0.8037	0.0795	0.0593	0.0533	2.7449	0.2566	0.0064	0.0501	0.1072
M0	0.0017	0.0730	0.0023	0.0002	0.0003	0.0659	0.0017	0.0001	0.0004	0.0012
Export	3.5720	0.0011	2.7255	1.8590	2.9830	31.6754	12.5498	81.8767	1.8274	2.7627
Import	0.9208	0.0009	0.8222	0.5269	0.7007	14.9890	3.3103	0.0520	23.9437	0.8679

Note: Values in the table are expressed in per cents. The deeper the shading is, the more significant the contribution.

## 6 Policy Implications

### 6.1 Macroeconomic Effects of QE

The recent GFC highlighted the limitations of inflation targeting in coping with large shocks, managing ZLB issues and facilitating a robust recovery. This triggered the use of an unconventional monetary policy tool, QE<sup>9</sup>. There is a broad consensus in the literature that QE is an effective tool for ensuring financial market stability; see [Meier \(2009\)](#), [Breedon et al. \(2012\)](#), [Joyce et al. \(2012\)](#) and [Haldane et al. \(2016\)](#) for the UK, and [Dell’Ariccia et al. \(2018\)](#) for a review of the literature for the euro area, the UK and Japan. In addition to its effects on financial markets, some studies have explored the macroeconomic effects of QE. Although the evidence in the previous literature is mixed, most research suggests that QE has a positive impact on output and inflation. However, there is less agreement on the magnitudes of these impacts; see [Giannone et al. \(2012\)](#) and [Hohberger et al. \(2019\)](#) for the euro area, [Chung et al. \(2011\)](#), [Chen et al. \(2012\)](#) and [Wu and Xia \(2016\)](#) for the US, [Girardin and Moussa \(2011\)](#) for Japan.

In the UK context, QE was first introduced during the GFC; [Figure 7](#) summarises the BoE’s monetary policy interventions from 2009 to 2021. [Joyce et al. \(2011\)](#) investigate the impact of the BoE’s QE1 (£200 billions of gilt purchases) using a structural VAR and show that it leads to a 2% increase in real GDP and a 1.5% rise in inflation. [Kapetanios et al. \(2012\)](#) use VAR models and find a peak impact of QE1 about 1.5% on real GDP and about 1.25% on inflation. [Bridges and Thomas \(2012\)](#) employ a simple money demand and supply framework to show that QE1 has a peak effect of about 2% on GDP and about 1% on inflation. [Falagiarda \(2014\)](#) employs a calibrated DSGE model to illustrate that QE1 yields a peak effect of 1.25% on real GDP and 0.49% on inflation. [Churm et al. \(2021\)](#) utilize a Bayesian VAR model to examine the BoE’s QE2 (£175 billion worth of gilt) and find it raises inflation by 0.6 pp and GDP growth by 0.5-0.8%. Using a Bayesian VAR model, [Weale and Wieladek \(2016\)](#) demonstrate that a QE announcement shock worth of 1% nominal GDP increases real GDP by 0.25% and CPI by 0.32%. [Lyu et al. \(2023\)](#) employ their estimated DSGE model and show a positive effect of QE on both inflation and output. In contrast to the above literature, [Salachas et al. \(2018\)](#) find an upward impact of QE on economic activity through a VAR model, but there is no evidence regarding its impact on prices. [Balatti et al. \(2016\)](#) find that QE significantly impacts only financial variables but not output and inflation from a Bayesian VAR model.

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9 In addition to QE, some economists, such as [Ball \(2014\)](#) and [Blanchard et al. \(2010\)](#), advocate setting a higher inflation target, e.g., 4%, to ease the monetary policy constraints of the ZLB. However, several studies argue that a high inflation target would cause significant costs and destabilise the macroeconomy, see, [Ascari and Sbordone \(2014\)](#), [Coibion et al. \(2012\)](#), [Ascari et al. \(2018\)](#), [Kara and Yates \(2021\)](#). These papers serve as a cautionary note to proposals that advocate targeting inflation at 4%.

Overall, the existing literature suggests a stimulatory effect of QE on both UK output and inflation. In our model specification, QE stimulates the economy by reducing the risk premium via its collateral role; and the policy regime switches between a normal scenario (with no ZLB) and a crisis scenario (with ZLB). To assess the effects of QE in these two scenarios, we fix the NK weights of prices and wages to their average weights to examine the impulse responses of output and inflation to a positive QE shock. As shown in [Figure 8](#), an increase in QE lowers the credit premium and increases output and inflation, which is broadly consistent with the literature. However, our state-dependent model suggests that the volatility of inflation in the ZLB periods appears to be beyond the control of monetary policy despite the intervention of QE policy. As illustrated in [Figure 9](#), inflation shows greater volatility during ZLB episodes. The monetary policy's inability to stabilise inflation during these ZLB periods results in increased price duration volatility, which further exacerbates price volatility and hence inflation volatility. As a result, ZLB events in the state-dependent model trigger significant fluctuations in inflation. This is in line with the findings of [Le et al. \(2021\)](#), who found that state-dependence interacts with the ZLB to produce high price and output volatility in ZLB episodes that cannot be controlled by QE, and that monetary policy rules need to be supplemented by a fiscal commitment to stop ZLB episodes in their tracks. Bearing this in mind, as well as the fact that the UK's recovery from the Great Recession had been sluggish despite massive QE injections and the implementation of a ZLB interest rate, we examine an alternative policy framework, in which an interest rate policy targets nominal GDP (NGDP), complemented by a fiscal backstop designed to prevent the occurrence of the ZLB. We investigate whether this framework improves the UK's macroeconomic outcomes relative to the baseline framework, which combines the Taylor Rule with QE.

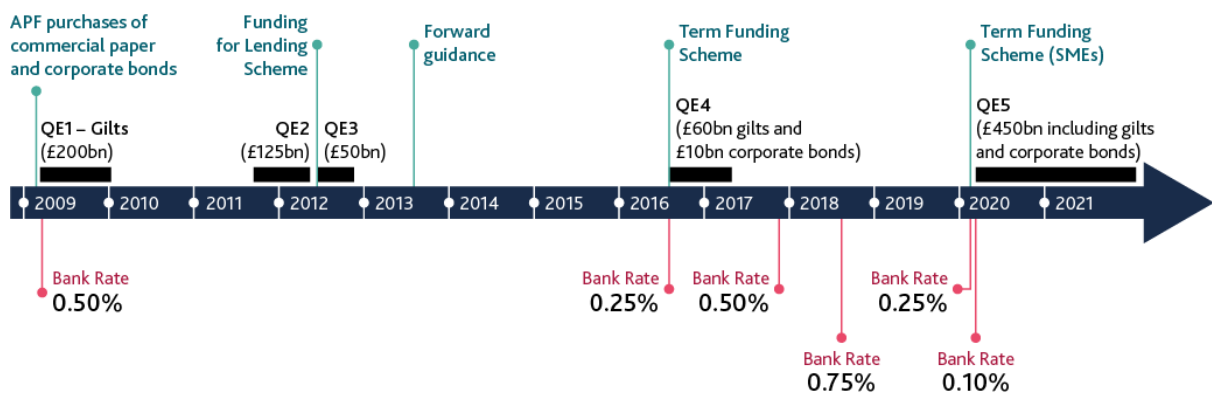


Figure 7: BoE's Monetary Policy Interventions between 2009-2021

Note: Source from [Bank of England \(2021\)](#).



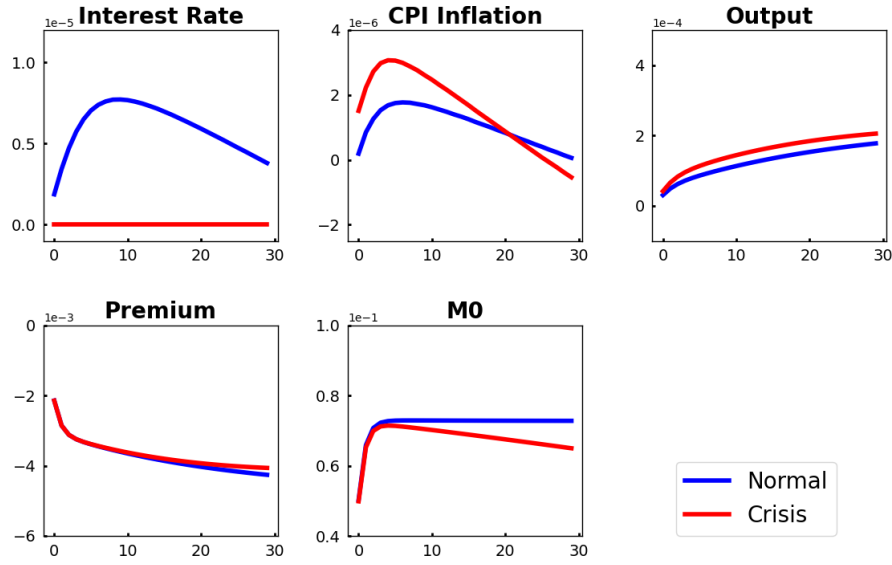


Figure 8: IRFs to a 5% QE Shock

Note: In the crisis regime, the Taylor Rule is replaced by an exogenous bound; hence the nominal interest rate is constant and equal to the bound. These IRFs are obtained by fixing the NK weights of prices and wages to their average weights.

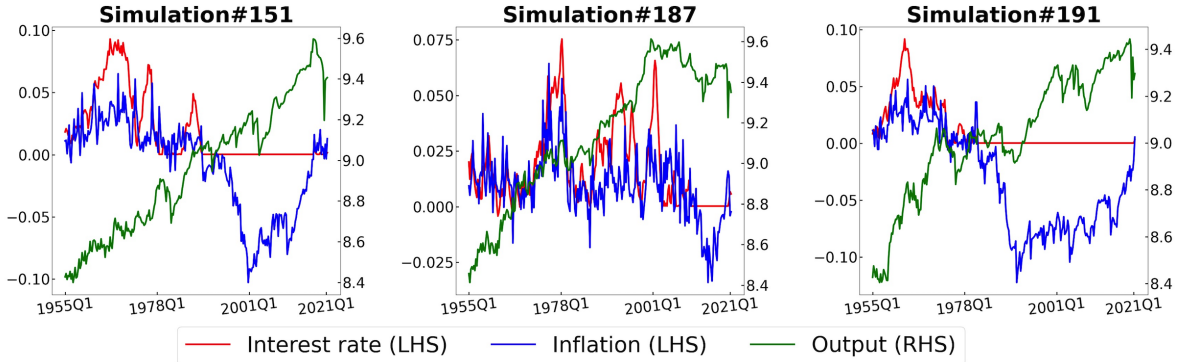


Figure 9: A Selection of Simulations - Inflation Fluctuations in ZLB

## 6.2 NGDP Targeting Supplemented by ZLB-suppressing Fiscal Policy

There is a growing interest in Market Monetarism, a macroeconomic theory advocating for central banks to adopt an NGDP level target to stabilise nominal incomes, as suggested by [Sumner \(2012\)](#), [Hendrickson \(2012\)](#) and [Woodford \(2012\)](#), among others. It involves the use of a simple feedback rule whereby the central bank adjusts policy rates in response to deviations in NGDP from the level target; policy is history-dependent and must make up for any past overshoots or shortfalls in economic activity to bring NGDP back to the fixed path. [Fackler and McMillin \(2020\)](#) use a VAR model and [Beckworth and Hendrickson \(2020\)](#), [Garín et al. \(2016\)](#), [Benchimol and Fourçans \(2019\)](#), [Billi \(2020; 2017\)](#), [Le et al. \(2016a; 2021\)](#) use DSGE models, suggesting that NGDP targeting could be

a desirable alternative to the current monetary policy framework in the US. In the context of open economies, there are only a few relevant studies of it. [Bhandari and Frankel \(2017\)](#) empirically test a simple theoretical model for India and find that NGDP targeting outperforms inflation targeting. [Benchimol \(2023\)](#) estimates a medium-scale small open economy model for the Israeli economy over the period 1992-2019. The author finds that Taylor-type rules are more appropriate than NGDP targeting rules when considering data-matching, but that NGDP targeting rules may be preferable in terms of various central bank objectives. [Le et al. \(2023b\)](#) employ an estimated open economy DSGE model and demonstrate that NGDP targeting is more effective than inflation targeting, and furthermore, a combination of NGDP targeting with an active M0 setting via open market operations further enhances the performance in stabilising the UK economy. [Hatcher \(2016\)](#) uses an overlapping generations model and finds that NGDP targeting makes taxes less volatile but raises average taxes compared to inflation targeting.

The NGDP targeting rule we examine is:

$$r_t = \rho_1 r_{t-1} + \rho_y (y_t + p_{d,t} - \bar{y}_t - \bar{p}_d) + \varepsilon_t \quad (30)$$

where  $\bar{y}_t + \bar{p}_d$  represents the target for nominal GDP,  $\bar{y}_t$  follows the real output generated by productivity,  $\bar{p}_d$  as steady price level is assumed to be constant and normalised to zero, and  $\rho_y$  is the partial elasticity of interest rate with respect to the nominal GDP deviation.  $y_t + p_{d,t} - \bar{y}_t - \bar{p}_d$  is the deviation of NGDP from the target, a combination of a stronger response to output gap ( $y_t - \bar{y}_t$ ) plus domestic price level targeting ( $p_{d,t} - \bar{p}_d$ ) in place of an inflation target. The former implies more output stability. The latter produces a more persistent response on interest rates to inflation shocks as it gets back to the same level, i.e., it produces a forward guidance effect and is more strongly in stabilising inflation. When faced with demand shocks, both price and output move in the same direction, hence requiring the same interest rate response. Compared to inflation targeting, NGDP targeting could stabilise both inflation and output more strongly due to the persistent/forward guidance effect. However, a dilemma arises in the event of supply shocks: price and output move in opposite directions. NGDP targeting could stabilise inflation but may worsen output. Because the NGDP target creates persistence in the interest rate response with a forward guidance effect, this is a powerful stabiliser of current inflation. It could worsen output response by stabilising current inflation more. We empirically check this later.

Additionally, there is an increasing recognition that monetary policy alone cannot bring the economy out of the liquidity trap and achieve price and economic stability; monetary-fiscal coordination is needed more than ever; see [Blanchard et al. \(2010\)](#), [Bhattarai and Egorov \(2016\)](#), [Portes and Wren-Lewis \(2015\)](#), [Prašćević and Ješić \(2019\)](#), [Nasir \(2021\)](#), [Le et al. \(2021; 2023b\)](#) and [Ascari et al. \(2023\)](#). As highlighted earlier,

our analysis of NGDP targeting is accompanied by a ZLB-suppressing fiscal rule to eliminate the greater inflation volatility during ZLB episodes induced by the interaction of state-dependence and the ZLB. Once the monetary policy is constrained by the ZLB, the fiscal policy serves as a backstop against the ZLB by preventing ZLB episodes from arising, thereby keeping the monetary policy of NGDP targeting effective. This enhances the stabilising role of monetary policy. Our baseline fiscal policy regime and fiscal ZLB-suppression regime are presented below:

**Baseline regime:**

$$\varepsilon_t^g = \rho_g \varepsilon_{t-1}^g + \sigma_{ga} \eta_t^\alpha + \eta_t^g, \quad \eta_t^g \sim N(0, \sigma_g^2) \quad \eta_t^\alpha \sim N(0, \sigma_a^2) \quad (31)$$

Where  $\varepsilon_t^g$  is the government spending shock,  $\eta_t^g$  and  $\eta_t^\alpha$  are the government spending and the productivity innovations, respectively.

**Fiscal ZLB-suppression regime:**

$$\varepsilon_t^g = \rho_g \varepsilon_{t-1}^g + \sigma_{ga} \eta_t^\alpha + \eta_t^g + f_t, \quad \eta_t^g \sim N(0, \sigma_g^2) \quad \eta_t^\alpha \sim N(0, \sigma_a^2) \quad (32)$$

Where  $f_t$  is the fiscal shock that pushes interest rate away from the ZLB.

### 6.3 Empirical Investigation Results

We combine the NGDP targeting rule with the fiscal ZLB-suppression policy to investigate whether shifting to this alternative policy framework would improve macroeconomic stability relative to the baseline framework of the Taylor Rule with QE. In the comparison, we consider the following criteria. First, the frequency of crises under the two policy frameworks; this measures the effectiveness of policies in preventing crises, viewed as severe recessions. Second, the variance of inflation. Third, the variance of output around a measure of trend output<sup>10</sup>. Fourth, the welfare cost, which is calculated as a weighted sum of the variances of inflation and output. We use simulation analysis to examine all these criteria to see whether the alternative policy framework produces attractive results.

In our estimated model, we replace the baseline policy framework with the NGDP targeting accompanied by the fiscal backstop framework and find that the rule of the following form can improve the performance of monetary policy:

$$r_t = 0.30r_{t-1} + 1.50(y_t + p_{d,t} - \bar{y}_t - \bar{p}_d) + \varepsilon_t \quad (33)$$

Table 5 summarises the average bootstrap simulation results for the two policy frameworks. Regarding the ability of each policy framework to reduce the number of crises, we

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<sup>10</sup> We create our trend output measure by adding the balanced growth path found in the data to the simulated productivity shocks.

examine the expected number of shallow and deep crises per 1000 years; shallow (or deep) crises are defined as small (or large) declines in output, where output does not return to its previous peak within five years. The simulations show that the ‘NGDP targeting with fiscal ZLB-suppression’ framework provides a modest improvement in reducing the number of shallow crises, and a significant enhancement in reducing the number of deep crises.

From a stabilisation perspective, our simulations show that the alternative framework yields a lower output variance and a significantly lower inflation variance than the baseline framework; there is a modest accompanying rise in the interest rate variance, as ZLB episodes of zero movement are eliminated while rates move strongly to implement the more demanding NGDP target. With respect to welfare costs, the alternative framework is associated with a significantly smaller welfare loss than the baseline framework. [Figure 10](#) presents some examples of the bootstrap simulations under the two frameworks. As observed, the alternative framework (in red) effectively prevents the occurrence of ZLB. Compared to the baseline framework (in blue), it stabilises inflation considerably and somewhat smooths output, although it appears to increase interest rates.

Regarding the price duration, the alternative framework generates a higher average NK price weight of 0.9874 compared to the baseline framework’s 0.9126, due to the fact that the lower the inflation volatility, the higher the NK weight of prices. As shown in [Figure 10](#), the alternative framework heavily stabilises inflation and therefore largely eliminates the destabilising behaviour in price/wage durations, leading to long price/wage durations.

We further compare the responses of both policy frameworks to demand and supply shocks separately. As [Table 6](#) illustrates, the alternative framework provides stronger stability to both inflation and output in scenarios of demand shocks. Conversely, [Table 7](#) shows that while the alternative framework stabilises inflation, it worsens the output response when the economy is subject to supply shocks. Under supply shocks, price and output move in contrary directions, requiring different interest rate responses. The alternative framework is a powerful stabiliser of current inflation, consequently worsening the output response by stabilising current inflation more. Given that output fluctuations are primarily driven by demand shocks (as shown in the variance decomposition analysis; see [Tables 3 and 4](#)), the alternative framework generates lower output and inflation variances overall.

Additionally, in our welfare measures, the variance of output is calculated around the measure of trend output. However, the trend path of real output might not be the true estimate of the flexprice model determined path. Thus, by employing a model-estimated equilibrium output path, we also check the robustness of the welfare measures under both policy frameworks. To get this alternative measure, we combine the balanced growth path with the simulated impact of all model shocks on output under the flexprice

model solution. The comparison of welfare using flexprice model solutions is presented in Table 8, indicating that the ‘NGDP targeting with fiscal ZLB-suppression’ framework still outperforms the baseline framework.

Our conclusions regarding the lower welfare costs and lower chances of crises from the alternative framework, in the context of the state-dependent model, are in line with the findings by Le et al. (2021) using a closed US DSGE model. Furthermore, our results of lower inflation and output variances in the alternative framework generally support the results of the literature employing DSGE models with fixed price/wage contracts; for example, Beckworth and Hendrickson (2020), Benchimol and Fourçans (2019) and Le et al. (2016a) for the US, and Le et al. (2023b) for the UK.

Table 5: Stability and Crises Comparison

	<b>Taylor Rule+QE</b>	<b>NGDP targeting+fiscal ZLB-suppression</b>
Shallow crises <sup>a</sup>	39.65	37.86
Deep crises <sup>a</sup>	30.94	24.62
Var(Output)	0.00107	0.00088
Var(Inflation)	0.0016	1.04e-04
Welfare <sup>b</sup>	0.00134	0.00049
Var(Interest rate)	0.00411	0.01059
Av. NK weight wage	0.9085	0.9831
Av. NK weight price	0.9126	0.9874

<sup>a</sup> Expected number of crises per 1000 years. Shallow and deep crises are defined as small and large declines in output, respectively, where output does not return to its previous peak within five years.

<sup>b</sup> The measurement of welfare costs is based on a weighted resource cost due to price variability and output variability:  $\text{welfare} = 0.5 * \text{var}(\pi) + 0.5 * \text{var}(y)$ .

Table 6: Stability Comparison in Response to Demand Shocks

	<b>Taylor Rule+QE</b>	<b>NGDP targeting+fiscal ZLB-suppression</b>
Var(Output)	1.77e-04	1.02e-04
Var(Inflation)	9.00e-06	8.18e-06
Welfare <sup>b</sup>	9.30e-05	5.51e-05

<sup>a</sup> The results were computed through bootstrapping the model and demand shocks (Taylor Rule and government spending shocks).

<sup>b</sup>  $\text{Welfare} = 0.5 * \text{var}(\pi) + 0.5 * \text{var}(y)$ .

Table 7: Stability Comparison in Response to Supply Shocks

	Taylor Rule+QE	NGDP targeting+fiscal ZLB-suppression
Var(Output)	3.60e-05	4.13e-05
Var(Inflation)	0.0013	7.22e-04
Welfare <sup>b</sup>	6.68e-04	3.82e-04

<sup>a</sup> The results were computed through bootstrapping the model and supply shocks (productivity and labour supply shocks).

<sup>b</sup> Welfare =  $0.5 * \text{var}(\pi) + 0.5 * \text{var}(y)$ .

Table 8: Welfare Comparison Based on Optimum Output Deviation in Flexprice Model

	Taylor Rule+QE	NGDP targeting+fiscal ZLB-suppression
Var(Output) <sup>a</sup>	0.00288	0.00146
Var(Inflation)	0.00160	1.04e-04
Welfare <sup>b</sup>	0.00224	0.00078

<sup>a</sup> Deviation from optimum output under flexprice model.

<sup>b</sup> Welfare =  $0.5 * \text{var}(\pi) + 0.5 * \text{var}(y)$ .

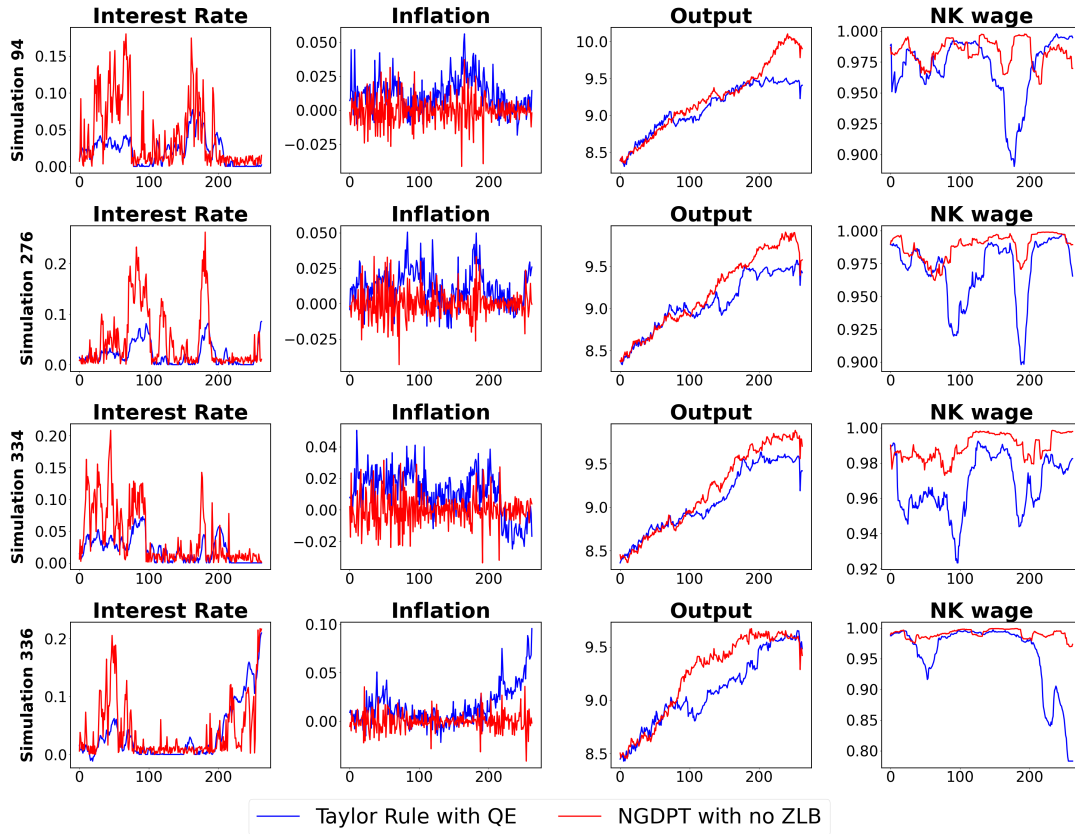


Figure 10: Simulation Comparison

## 7 Conclusion

Despite the considerable micro-level evidence of state-dependent price/wage duration, there is a noticeable scarcity of literature examining it at the macro level. Among the few macro-level studies conducted, all have been focused on closed economy DSGE models in the US context. This paper fills this gap by studying how macroeconomic behaviour is affected by state-dependence in an open economy context. We extend the state-dependent DSGE model of [Le et al. \(2021\)](#) for the US economy to an open economy setting for the UK and investigate whether there is macro-level evidence to corroborate the micro-level evidence of state-dependence. Our Indirect Inference estimation and test results indicate that the state-dependent model fits the dynamic behaviour of the key variables over the sample period 1955-2021. Our state-dependent model produces behaviour that is consistent with the literature, i.e. in periods of high inflation, prices respond to shocks quickly and with low persistence, leading to a smaller real impact of monetary shocks. Furthermore, the price/wage contract durations fluctuate with the state of the economy (inflation) throughout the whole sample.

In the state-dependent scenario, apart from directly responding to shocks, monetary policy also determines the price/wage stickiness of the economy, which in turn indirectly affects the response to these shocks. As a result, under the interaction of state-dependence and ZLB, monetary-fiscal coordination is needed to stabilise the economy, as monetary policy alone cannot achieve economic stability during ZLB scenarios. By examining a coordinated monetary-fiscal policy framework, i.e., an interest rate policy that targets NGDP complemented by a fiscal ZLB-suppression rule, we find that this alternative policy framework outperforms the baseline framework of the Taylor Rule with QE in terms of its ability to avoid crises and decrease welfare costs; the regime implies a higher interest rate variance as the ZLB is avoided and rates respond more strongly to the demanding NGDP target. Notably, this alternative framework provides a stronger stabilisation of inflation and output under demand shocks than the baseline framework; due to its power in stabilising prices, it worsens the output response to supply shocks by holding down the price response. But overall it enhances the stability of both output and inflation because demand shocks predominate. Additionally, the alternative framework significantly stabilises inflation, which in turn stabilises price/wage durations, resulting in long price/wage durations.

Practical questions remain as to whether this alternative regime can be implemented politically. The NGDP target implies keeping interest rates away from normal rates for long periods after inflation has returned to normal; this is vulnerable to time-inconsistency, because of the temptation to bring rates back down. The fiscal backstop requires sharp changes in government borrowing which may be hard to implement in the face of market opinion. These questions of practical implementation no doubt account for the lack of

examples of these policies around the world. What our model reveals however is that they have potential benefits if such practical obstacles can be overcome.



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## Appendix A. Log-linearised Model List

Consumption Euler Equation

$$c_t = \frac{\frac{h}{\gamma}}{1 + \frac{h}{\gamma}} c_{t-1} + \frac{1}{1 + \frac{h}{\gamma}} E_t c_{t+1} + \frac{(\sigma_c - 1) \frac{W_* L_*}{C_*}}{\left(1 + \frac{h}{\gamma}\right) \sigma_c} (l_t - E_t l_{t+1}) - \frac{1 - \frac{h}{\gamma}}{\left(1 + \frac{h}{\gamma}\right) \sigma_c} (r_t - E_t \pi_{t+1}^{cpi}) + \varepsilon_t^b \quad (\text{A1})$$

Investment Euler Equation

$$i_t = \frac{1}{1 + \beta \gamma^{(1-\sigma_c)}} i_{t-1} + \frac{\beta \gamma^{1-\sigma_c}}{1 + \beta \gamma^{1-\sigma_c}} E_t i_{t+1} + \frac{1}{(1 + \beta \gamma^{(1-\sigma_c)}) \gamma^2 \varphi} qq_t + \varepsilon_t^i \quad (\text{A2})$$

Production Function

$$y_t = \phi [\alpha k_t^s + (1 - \alpha) l_t + \varepsilon_t^a] \quad (\text{A3})$$

Capital Accumulation Equation

$$k_t = \left(\frac{1 - \delta}{\gamma}\right) k_{t-1} + \left(1 - \frac{1 - \delta}{\gamma}\right) i_t + \left(1 - \frac{1 - \delta}{\gamma}\right) ((1 + \beta \gamma^{(1-\sigma_c)}) \gamma^2 \varphi) \varepsilon_t^i \quad (\text{A4})$$

Current Capital Service

$$k_t^s = k_{t-1} + z_t \quad (\text{A5})$$

Capital Utilisation

$$z_t = \frac{1 - \psi}{\psi} r k_t \quad (\text{A6})$$

Capital Arbitrage (Tobin' Q) Equation

$$qq_t = \frac{1 - \delta}{1 - \delta + R_*^K} E_t qq_{t+1} + \frac{R_*^K}{1 - \delta + R_*^K} E_t r k_{t+1} - E_t cy_{t+1} \quad (\text{A7})$$

Demand for Labour

$$l_t = -w_t^h + \left(1 + \frac{1 - \psi}{\psi}\right) r k_t + k_{t-1} \quad (\text{A8})$$

External Finance Premium

$$\text{prem}_t = E_t cy_{t+1} - (r_t - E_t \pi_{t+1}^{cpi}) = \chi (qq_t + k_t - n_t) - \vartheta m_t^0 + \varepsilon_t^{\text{prem}} \quad (\text{A9})$$

Net Worth Evolution

$$n_t = \frac{K}{N} (cy_t - E_{t-1} cy_t) + E_{t-1} cy_t + \theta n_{t-1} + \varepsilon_t^{nw} \quad (\text{A10})$$

Consumption of Entrepreneurs

$$c_t^e = n_t \quad (\text{A11})$$

### Hybrid Domestic Price Setting (Weighted Home Inflation)

$$(\pi_t^h)^{NK} : \quad \pi_t^h = \frac{\beta\gamma^{1-\sigma_c}}{1 + \beta\gamma^{(1-\sigma_c)}l_p} E_t \pi_{t+1}^h + \frac{l_p}{1 + \beta\gamma^{(1-\sigma_c)}l_p} \pi_{t-1}^h - \frac{1}{1 + \beta\gamma^{(1-\sigma_c)}l_p} \left( \frac{(1 - \beta\gamma^{(1-\sigma_c)}\xi_p)(1 - \xi_p)}{\xi_p(1 + (\phi_p - 1)\epsilon_p)} \right) (\alpha r k_t + (1 - \alpha)w_t^h - \varepsilon_t^a) + \varepsilon_t^p \quad (A12)$$

$$\text{NC Marginal Product of Labour } (\pi_t^h)^{NC} : r k_t = \frac{1}{\alpha} [-(1 - \alpha)w_t^h + \varepsilon_t^a] \quad (A13)$$

$$(\pi_t^h)^{hybrid} = \omega^p (\pi_t^h)^{NK} + (1 - \omega^p) (\pi_t^h)^{NC} \quad (A14)$$

### Hybrid Real Consumer Wage Setting

$$(w_t^c)^{NK} : \quad w_t^c = \frac{\beta\gamma^{1-\sigma_c}}{1 + \beta\gamma^{1-\sigma_c}} E_t w_{t+1}^c + \frac{1}{1 + \beta\gamma^{1-\sigma_c}} w_{t-1}^c + \frac{\beta\gamma^{1-\sigma_c}}{1 + \beta\gamma^{1-\sigma_c}} E_t \pi_{t+1}^{cpi} - \frac{1 + (\beta\gamma^{(1-\sigma_c)}l_w)}{1 + \beta\gamma^{1-\sigma_c}} \pi_t^{cpi} + \frac{l_w}{1 + \beta\gamma^{1-\sigma_c}} \pi_{t-1}^{cpi} - \frac{1}{1 + \beta\gamma^{1-\sigma_c}} \left( \frac{(1 + \beta\gamma^{(1-\sigma_c)}\xi_w)(1 - \xi_w)}{\xi_w(1 + (\phi_w - 1)\epsilon_w)} \right) \left( w_t^c - \sigma_l l_t - \left( \frac{1}{1 - \frac{h}{\gamma}} \right) \left( c_t - \frac{h}{\gamma} c_{t-1} \right) \right) + \varepsilon_t^{wNK} \quad (A15)$$

$$\text{NC Labour Supply } (w_t^c)^{NC} : w_t^c = \sigma_l l_t + \left( \frac{1}{1 - \frac{h}{\gamma}} \right) \left( c_t - \frac{h}{\gamma} c_{t-1} \right) - (\pi_t^{cpi} - E_{t-1} \pi_t^{cpi}) + \varepsilon_t^{wNC} \quad (A16)$$

$$w_t^{hybrid} = \omega^w (w_t^c)^{NK} + (1 - \omega^w) (w_t^c)^{NC} \quad (A17)$$

### Monetary Policy for Normal Regime (Non-crisis)

$$\text{For } r_t > 0.025\% \begin{cases} r : r_t = \rho r_{t-1} + (1 - \rho) (r_p \pi_t^{cpi} + r_y y_t) + r_{\Delta y} (y_t - y_{t-1}) + \varepsilon_t^r \\ M0 : m_t^0 = m_{t-1}^0 + \vartheta_1 (m_t^2 - m_{t-1}^2) + \varepsilon_t^{m0, nocrisis} \\ M2 : m_t^2 = (1 + \nu - \mu) k_t + \mu m_t^0 - \nu n_t, \quad \nu = \frac{N}{M2}, \mu = \frac{M0}{M2} \end{cases} \quad (A18)$$

### Monetary Policy for Crisis Regime

$$\text{For } r_t \leq 0.025\% \begin{cases} M0 : m_t^0 = m_{t-1}^0 + \vartheta_2 (prem_t - prem^*) + \varepsilon_t^{m0, crisis} \\ r : r = 0.025\% \end{cases} \quad (A19)$$

Real Uncovered Interest Rate Parity

$$q_t = E_t q_{t+1} + \left( r_t^f - E_t \pi_{t+1}^f \right) - \left( r_t - E_t \pi_{t+1}^{cpi} \right) \quad (\text{A20})$$

Import Demand

$$im_t = \ln \omega + c_t - \sigma q_t + \varepsilon_t^{im} \quad (\text{A21})$$

Export Demand

$$ex_t = \ln \omega^f + c_t^f + \sigma^f q_t + \varepsilon_t^{ex} \quad (\text{A22})$$

Net Foreign Assets Evolution

$$b_t^f = \left( 1 + r_{t-1}^f \right) b_{t-1}^f + \frac{EX}{Y} (ex_{t-1} - q_{t-1}) - \frac{IM}{Y} im_{t-1} \quad (\text{A23})$$

CPI Inflation

$$\pi_t^{cpi} = \pi_t^h + \frac{\omega}{1 - \omega} \Delta q_t \quad (\text{A24})$$

The Wedge Between the Real Consumer Wage and Real Producer Wage

$$w_t^h = w_t^c + \frac{\omega}{1 - \omega} q_t \quad (\text{A25})$$

Aggregate Resource Constraint

$$y_t = \frac{C}{Y} c_t + \frac{I}{Y} i_t + R_*^K k_y \frac{1 - \psi}{\psi} r k_t + \frac{C^e}{Y} c_t^e + \frac{EX}{Y} ex_t - \frac{IM}{Y} im_t + \varepsilon_t^g \quad (\text{A26})$$

**Exogenous Processes:**

Government spending shock:  $\varepsilon_t^g = \rho_g \varepsilon_{t-1}^g + \sigma_{ga} \eta_t^a + \eta_t^g$

Preference shock:  $\varepsilon_t^b = \rho_b \varepsilon_{t-1}^b + \eta_t^b$

Productivity shock:  $(\varepsilon_t^a - \varepsilon_{t-1}^a) = \rho_a (\varepsilon_t^a - \varepsilon_{t-1}^a) + \eta_t^a$

Investment-specific shock:  $\varepsilon_t^i = \rho_i \varepsilon_{t-1}^i + \eta_t^i$

Taylor Rule shock:  $\varepsilon_t^r = \rho_r \varepsilon_{t-1}^r + \eta_t^r$

Price mark-up shock:  $\varepsilon_t^p = \rho_p \varepsilon_{t-1}^p + \eta_t^p$

NK wage mark-up shock:  $\varepsilon_t^{wNK} = \rho_w^{nk} \varepsilon_{t-1}^{wNK} + \eta_t^{wNK}$

NC wage mark-up (labour supply) shock:  $\varepsilon_t^{wNC} = \rho_w^{nc} \varepsilon_{t-1}^{wNC} + \eta_t^{wNC}$

External finance premium shock:  $\varepsilon_t^{prem} = \rho_{pr} \varepsilon_{t-1}^{prem} + \eta_t^{prem}$

Net worth shock:  $\varepsilon_t^{nw} = \rho_{nw} \varepsilon_{t-1}^{nw} + \eta_t^{nw}$

Export demand shock:  $\varepsilon_t^{ex} = \rho_{ex} \varepsilon_{t-1}^{ex} + \eta_t^{ex}$

Import demand shock:  $\varepsilon_t^{im} = \rho_{im} \varepsilon_{t-1}^{im} + \eta_t^{im}$

Exogenous foreign consumption process:  $c_t^f = \rho_c^f c_{t-1}^f + \eta_t^{cf}$

Exogenous foreign interest rate process:  $r_t^f = \rho_r^f r_{t-1}^f + \eta_t^{rf}$

Money supply shock (crisis shock):  $\varepsilon_t^{m0, \text{crisis}} = \rho_{m0, \text{crisis}} \varepsilon_{t-1}^{m0, \text{crisis}} + \eta_t^{m0, \text{crisis}}$

Money supply shock (non-crisis shock):  $\varepsilon_t^{m0, \text{nocrisis}} = \rho_{m0, \text{nocrisis}} \varepsilon_{t-1}^{m0, \text{nocrisis}} + \eta_t^{m0, \text{nocrisis}}$

# Appendix B. Shock and Residual Histories, Data and Fixed Parameters

Figure B1, Figure B2, Table B1, Table B2 and Table B3.

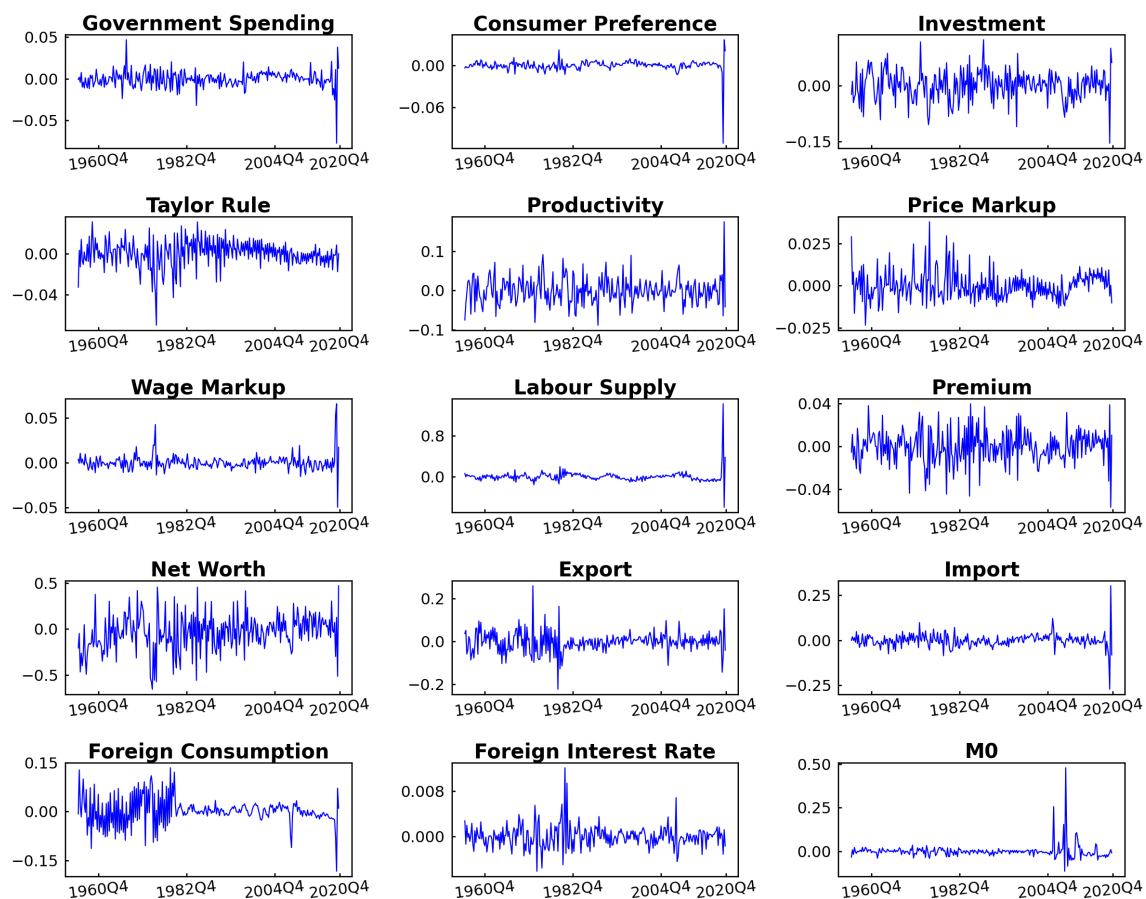


Figure B1: Model Implied Shock Histories

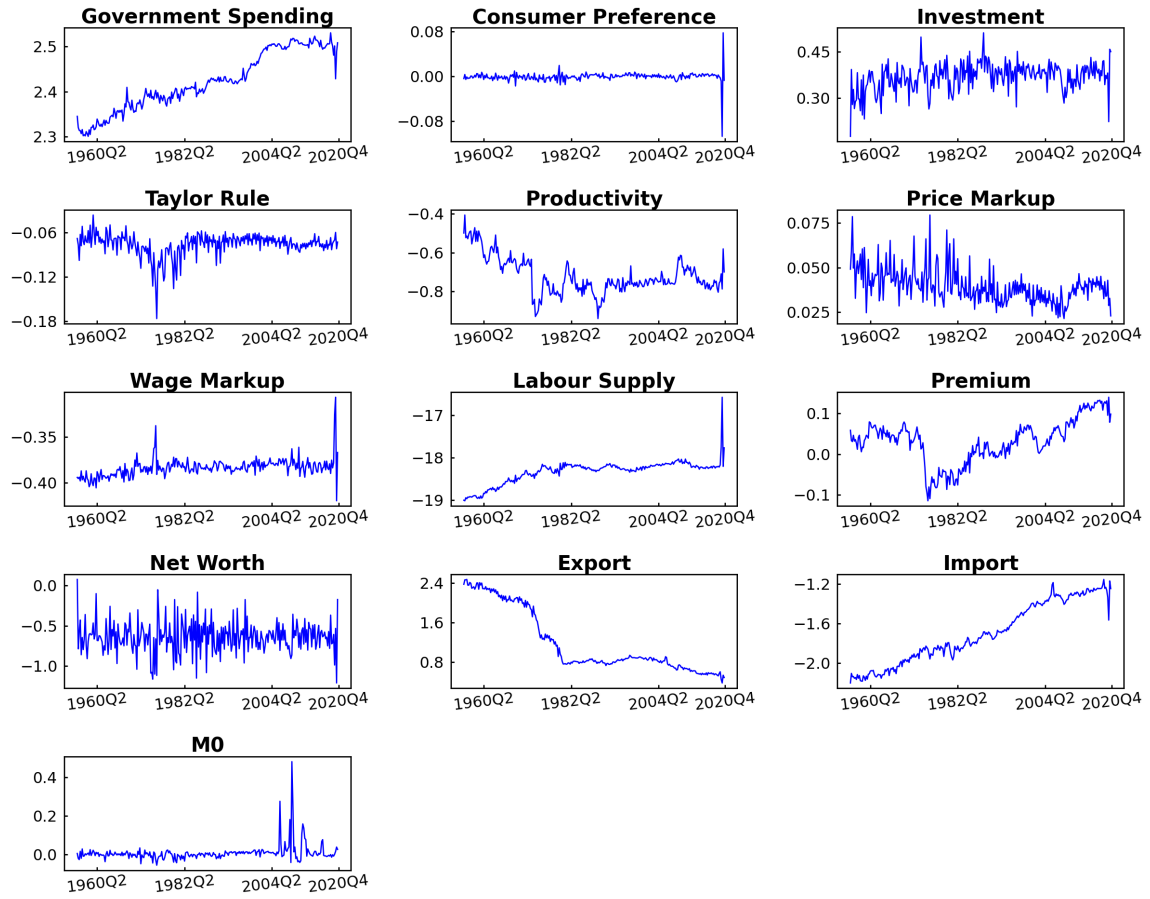


Figure B2: Model Implied Residual Histories

Table B1: Stationarity of Residuals and AR(1) Coefficients

Shock	AR(1) Coefficient	ADF P-value <sup>a</sup>	KPSS Statistic <sup>b</sup>	Conclusion
Pre-1972 Period				
Government	0.3585	0.0000***	0.0854	Stationary
Preference	-0.2783	0.0000***	0.1238	Stationary
Investment	-0.1132	0.0308**	0.6316 <sup>++</sup>	Trend Stationary
Taylor Rule	0.0307	0.0014***	0.6141 <sup>++</sup>	Trend Stationary
Productivity	-0.3941	0.1612	0.1464 <sup>++</sup>	Non-stationary
Price mark-up	-0.0192	0.0000***	0.3944 <sup>+</sup>	Trend Stationary
Wage mark-up	0.0686	0.0350**	0.0851	Stationary
Labour supply	0.4913	0.2965	0.1038	Trend Stationary
Premium	0.6076	0.0511*	0.2093	Stationary
Net worth	-0.0412	0.0001***	0.1274	Stationary
M0(crisis)	-0.2462	0.0001***	0.0989	Stationary
M0(noncrisis)	-0.2326	0.0002***	0.1514	Stationary
Export	0.1119	0.0674*	0.0873	Stationary
Import	0.5567	0.2924	0.3056 <sup>+++</sup>	Trend Stationary <sup>c</sup>
Post-1972 Period				
Government	0.8041	0.1294	0.1781 <sup>++</sup>	Trend Stationary <sup>c</sup>
Preference	-0.3736	0.0000***	0.2902	Stationary
Investment	0.1322	0.0000***	0.0855	Stationary
Taylor Rule	0.3915	0.0494**	0.7264 <sup>++</sup>	Trend Stationary
Productivity	-0.3772	0.0146**	0.7541 <sup>+++</sup>	Non-stationary <sup>d</sup>
Price mark-up	0.1674	0.0079***	0.6376 <sup>++</sup>	Trend Stationary
Wage mark-up	0.1258	0.0000***	0.2863	Stationary
Labour supply	0.3248	0.0000***	0.0744	Stationary
Premium	0.7726	0.0004***	0.0699	Stationary
Net worth	-0.0780	0.0000***	0.1136	Stationary
M0(crisis)	0.3128	0.0000***	0.8033 <sup>+++</sup>	Trend Stationary
M0(noncrisis)	0.3113	0.0000***	0.7934 <sup>+++</sup>	Trend Stationary
Export	0.9234	0.0001***	0.1997 <sup>++</sup>	Trend Stationary
Import	0.7643	0.0153**	0.2017 <sup>++</sup>	Trend Stationary

<sup>a</sup> For the Augmented Dickey-Fuller (ADF) test, \*\*\*, \*\* and \* denote rejection of the unit root null at 1%, 5% and 10% significance levels, respectively.

<sup>b</sup> For the Kwiatkowski–Phillips–Schmidt–Shin (KPSS) test, <sup>+++</sup>, <sup>+</sup>, and <sup>+</sup> indicate rejection of the stationary null at 1%, 5% and 10% significance levels, respectively.

<sup>c</sup> These residuals are deemed trend stationary because their AR(1) coefficients are less than 1, suggesting that the impact of shocks diminish over time.

<sup>d</sup> Regarding the stationarity of the productivity residual for the post-1972 period, while the ADF test suggests it is stationary, the KPSS test rejects the null hypothesis of stationarity at the 1% significance level. For further clarity, we employed the DF-GLS test, which also indicates nonstationary. Hence, in light of both empirical results and theoretical consideration, we conclude that the productivity residual is non-stationary in the post-1972 period.

Table B2: Model Variable Construction and Data Sources

Variable	Symbol	Definition	Source
Output	$Y$	$\frac{\text{Gross domestic product: CVM}}{\text{Working population}}$	ONS
Consumption	$C$	$\frac{\text{Household final consumption expenditure: CVM}}{\text{Working population}}$	ONS
Investment	$I$	$\frac{\text{Total fixed capital formation: CVM} + \text{Changes in inventories: CVM}}{\text{Working population}}$	ONS
CPI inflation	$\pi^{cpi}$	Percentage change in CPI	ONS
Nominal interest rate	$R$	$\frac{3 \text{ months Treasury Bills rate}}{4} / 100$	OECD and Financial Times
Labour hours	$L$	Average actual weekly hours worked per employee	University of Groningen PWT, ONS
Real consumer wage	$W^c$	$\frac{\text{Wage and salaries}}{\text{Total hours worked} * \text{CPI}}$	ONS
External finance premium	$PM$	$\frac{\text{Bank lending rate} - 3 \text{ month Treasury bills rate}}{4} / 100$	Refinitiv DataStream
Real lending rate	$CY$	$\frac{\text{Bank lending rate}}{4 * 100} - \text{one period ahead CPI inflation}$	Refinitiv DataStream
Net worth	$N$	$\frac{\text{FTSE all share index}}{\text{CPI}}$	Refinitiv DataStream
M2	$M2$	$\frac{\text{M2 money stock, CP}}{\text{CPI} * \text{Working population}}$	FRED, BoE
M0	$M0$	$\frac{\text{Money supply M0, CP}}{\text{CPI} * \text{Working population}}$	BoE
Export	$EX$	$\frac{\text{Total exports: CVM}}{\text{Working population}}$	ONS
Import	$IM$	$\frac{\text{Total imports: CVM}}{\text{Working population}}$	ONS
Real Exchange rate	$Q$	$\frac{1}{\text{Sterling real effective exchange rate index}}$	BoE, BIS
Net foreign bond position	$B^f$	Current account balance as per cent of GDP	ONS
Capital	$K$	Derived from capital accumulation equation	Calculation
Price of capital	$P^k$	Derived from investment Euler equation	Calculation
Capital rental rate	$R^k$	Derived from labour demand equation	Calculation

\* ONS, BoE, FRED, OECD, and BIS are short for the Office for National Statistics, the Bank of England, the Federal Reserve Economic Data, the Organization for Economic Co-operation and Development, and the Bank for International Settlement, respectively.

\* CVM: Chained Volume Measure; CP: Current Price.

\* Two foreign variables are treated as exogenous AR(1) processes and constructed following [Dong et al. \(2019\)](#): the foreign real interest rate ( $r^f$ ) is the weighted average real interest rates for US (60%), Germany (19%) and Japan (21%); and the foreign consumption demand ( $C^f$ ) is world exports of goods and services.

\* The working population is calculated as the sum of “total claimant count (ONS)” and “work force jobs (ONS)” .

Table B3: Parameters Fixed Throughout Study

Symbol	Description	Value	Source
$\beta$	Quarterly discount rate	0.990	SW(07)
$\delta$	Quarterly capital depreciate rate	0.025	SW(07)
$\theta$	Survival rate of firms	0.970	BGG
$\gamma$	Quarterly trend growth rate	1.004	SW(07)
$\epsilon_w$	Kimball aggregator curvature for wages	10.00	SW(07)
$\epsilon_p$	Kimball aggregator curvature for prices	10.00	SW(07)
$(1 - \omega)$	Home bias in consumption	0.700	<a href="#">Meenagh et al. (2010)</a>
$(1 - \omega^f)$	Foreign equivalent of $\omega$	0.700	<a href="#">Meenagh et al. (2010)</a>