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Macroeconomic Fluctuations Under Various Frictions: A Comparative Study Using DSGE Models

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Abstract

Dynamic Stochastic General Equilibrium (DSGE) models are the leading tool for analysing the dynamic responses of an economy to various shocks and frictions. These models provide an extensive framework for examining the impact of different shocks, such as changes in technology or monetary policy, by capturing the interactions between multiple sectors of the economy. The incorporation of both nominal and real rigidities, enables these models to accurately reflect the gradual adjustments observed in real economies. Despite their comprehensive design, traditional DSGE models often fail to incorporate labour market and financial frictions, which limits their ability to fully capture the complexity of economic dynamics. This study demonstrates that integrating these frictions causes substantial changes in the dynamics and outcomes of DSGE models, suggesting that standard models may have overlooked significant economic interactions. For example, modelling wages as an equilibrium outcome and introducing a financial accelerator mechanism has a significant impact on inflation and investment responses. Furthermore, varying key parameters that govern nominal and real frictions reveals additional insight into the differing dynamics of the models. These findings challenge the adequacy of traditional models and accentuate the necessity for more comprehensive frameworks in order to gain meaningful understanding of how economies respond to various shocks. Further, incorporating these frictions not only enhances the precision of DSGE models but also has significant implications for forecasting and policy-making. In conclusion, these results underscore the necessity of evolving macroeconomic models to include more complex frictions, so they accurately reflect real economies.

Abstract Italian

Fluttuazioni macroeconomiche in presenza di diverse rigidità: Uno studio comparativo con modelli DSGE

I modelli dinamici stocastici di equilibrio generale (dynamic stochastic general equilibrium, DSGE) rappresentano lo strumento principale per l'analisi delle risposte dinamiche di un'economia a vari shock e frizioni. Tali modelli forniscono un quadro completo per esaminare l'impatto di diversi shock, come cambiamenti tecnologici o di politica monetaria, catturando le interazioni tra più settori dell'economia. L'inclusione di rigidità sia nominali che reali consente a questi modelli di riflettere accuratamente i graduali aggiustamenti osservati nelle economie reali. Nonostante la loro struttura articolata, i modelli DSGE tradizionali spesso non incorporano le rigidità del mercato del lavoro e della finanza, il che limita la loro capacità di cogliere appieno la complessità delle dinamiche economiche. Questo studio dimostra che l'aggiunta di tali frizioni, determina cambiamenti sostanziali nelle dinamiche e nei risultati dei modelli DSGE, suggerendo che i modelli standard potrebbero aver trascurato interazioni economiche significative. Ad esempio, la modellizzazione dei salari come risultato di equilibrio e l'introduzione di un meccanismo di accelerazione finanziaria hanno un impatto significativo sulle risposte di inflazione ed investimenti. Inoltre, variando i parametri chiave che regolano le frizioni nominali e reali si ottengono ulteriori informazioni sulle diverse dinamiche dei modelli. Questi risultati mettono in discussione l'adeguatezza dei modelli tradizionali e accentuano la necessità di schemi più completi per comprendere in modo significativo come le economie rispondono ai vari shock. Inoltre, l'integrazione di queste frizioni non solo migliora la precisione dei modelli DSGE, ma ha anche implicazioni significative per le previsioni e la definizione delle politiche. In conclusione, questi risultati sottolineano la necessità di evolvere i modelli macroeconomici per includere rigidità più complesse, così da riflettere accuratamente le economie reali.

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List of Acronyms

AOB Alternating Offer Bargaining.

CET Christiano et al. (2016).

CMR Christiano et al. (2014).

DSGE Dynamic Stochastic General Equilibrium.

IRFs Impulse Response Functions.

NK New Keynesian.

SW Smets and Wouters (2007).

1 Introduction

Dynamic Stochastic General Equilibrium (DSGE) models are the standard workhorses for modern macroeconomic analysis as they incorporate a wide range of frictions and structural parameters (Gelain et al., 2010). This allows them to capture how economies respond to changes in monetary policy, technology and other external disturbances (Smets and Wouters, 2007). Despite their widespread use, DSGE models have been challenged, for example by Lucas (1976), who argues against using statistical relationships from past data to predict the effects of new policies, as the estimated parameters will change in response to policy changes (Ljungqvist, 2008; Lucas Jr, 1976). In addition, DSGE models have been criticised as they do not account for labour market and financial frictions, which limits their ability to replicate real world dynamics (Christiano et al., 2010a; Trigari, 2006).

Given these limitations and the fact that it is very difficult to implement all frictions in a single model, this study aims to compare three DSGE models, each with different implemented frictions and parameter calibrations. The models analysed include a standard DSGE model, representative of which is the widely used model of Smets and Wouters (2007), hereafter referred to as SW. To consider a model that integrates labour market frictions, Christiano et al. (2016) (CET) which incorporates a search and matching model and alternating offer bargaining (AOB), is also evaluated. Finally, Christiano et al. (2014), henceforth CMR, is part of the comparison to represent a model with financial frictions as it implements a financial accelerator mechanism developed by in Bernanke et al. (1999), including agency problems such as asymmetric information and costly monitoring. By analysing how these models respond to the same set of shocks, this study explores the implications associated with labour and financial frictions and provides insights into how they affect macroeconomic outcomes. In addition, a sensitivity analysis will further investigate how and which key parameters drive these frictions. Therefore, this comparative analysis will highlight the key mechanisms that may be overlooked by standard DSGE models and guide future research in macroeconomic modelling as well as policy-making.

The analysis includes responses to three different shocks: a monetary policy shock, a neutral technology shock and an investment-specific technology shock. Incorporating monetary policy shocks enhances the understanding of economic dynamics, allowing the analysis of how unexpected interest rate changes affect key indicators such as inflation, output, consumption and investment (Christiano et al., 2016; Jarociński and Karadi, 2020). Further, monetary policy shocks can have distinct effects across the models. For example, in the CET model, these disturbances have a contemporaneous impact only on the interest rate which causes hump-shaped responses in macroeconomic variables (Christiano et al., 2016). Moreover, this shock reveals the characteristic feature of the model, wage inertia, which plays a crucial role in determining the inflation reaction (Christiano et al., 2016). These results provide insights into monetary policy transmission mechanisms and are suitable to compare the impacts of differing levels of stickiness which is studied in the second part of the analysis.

Neutral technology shocks, often referred to as total factor productivity shocks (Justiniano et al., 2010), are included in the analysis as they are expected to be a great driver of business cycles (King and Rebelo, 1999). These technology shocks affect key variables such as hours worked, output, wages, and inflation by impacting equations characterising marginal costs, labour productivity, production functions and technology growth, ultimately leading to lower marginal costs and higher labour productivity (Ireland, 2004). The supply shocks are able to illustrate the varying effects across three models and their impulse response functions (IRFs) on output and hours worked (Fisher, 2006). The latter effect is particularly controversial among researchers. On the one hand, it is argued that nominal and real rigidities result in an immediate decrease in hours worked following positive productivity shocks (Francis and Ramey, 2005; Gali, 1999;

Galí and Rabanal, 2004). On the other hand, there is empirical evidence that contradicts this assumption and may even indicate a positive effect on hours worked (Christiano et al., 2003; Dedola and Neri, 2007; Peersman and Straub, 2009). In addition, there is evidence that inflation is more responsive to technology shocks than to monetary policy shocks, making it crucial to include this type of disturbance as well (Paciello, 2011).

Finally, investment-specific technology shocks are included in this analysis to illustrate their role in affecting the intertemporal margin and driving economic growth (Fisher, 2006; Greenwood et al., 1997). These demand shocks impact the accumulation of installed capital, which is influenced not only by the flow of investment but also by the relative efficiency of these investment expenditures, as captured by the investment-specific technology disturbance. This disturbance therefore affects both the Euler equation for investment and the law of motion for capital (Smets and Wouters, 2007). Moreover, investment-specific technology shocks contribute to composite technology growth, revealing that neutral technology shocks are not the only source of technological change (Christiano et al., 2016, 2014; Fisher, 2006). Certain assumptions associated with investment-specific technological change further demonstrate its significance. First, it is assumed that the only shock influencing the price of investment relative to consumption in the long run is the investment-specific innovation (Christiano et al., 2016; Fisher, 2006). Second, the innovations to both the neutral technology shock and the investment-specific technology shock are the only shocks that affect labour productivity in the long run (Christiano et al., 2016).

The parameters examined in detail in the sensitivity analysis represent both nominal rigidities, by price and wage stickiness, and real rigidities, by investment adjustment costs. The Calvo (1983) parameters for prices and wages capture the degree of stickiness within a model, as they determine the frequency with which agents can adjust their prices or wages (Romer, 2018). A higher Calvo parameter indicates more sticky prices or wages, meaning that they are adjusted less frequently in response to economic fluctuations (Henkel, 2020). All the models studied incorporate price setting subject to Calvo-style frictions. Similar considerations apply to wage stickiness; however, the CET model uses alternating offer bargaining, which distinguishes it from the assumption of exogenously sticky wages in the SW and CMR models. Furthermore, in the SW and CMR models, firms that cannot adjust their prices and wages index them partially to past inflation rates, in contrast to the CET model, which challenges the indexation assumption (Christiano et al., 2016). The implications of the Calvo parameters have important effects on the economy. Notably, higher rigidity in prices and wages alters the impulse response functions to shocks by revealing different mechanisms across the models (Caballero and Engel, 2007). For instance, when wages and prices are flexible, the real interest rate responds more robustly to shocks than under rigidities (Christiano et al., 2010b). Overall, these variations in stickiness have multiple implications for economic dynamics, including the speed of adjustment to equilibrium and the transmission of monetary policy (Henkel, 2020; Smets and Wouters, 2007).

Investment adjustment costs define the expenses incurred when the level of investment changes (Torres, 2020). These costs are one of the most important real frictions for enhancing a model's ability to accurately reflect real-world dynamics (Christiano et al., 2005). Investment adjustment costs affect the dynamics of capital accumulation, which in turn influences the long-term growth of the economy (Smets and Wouters, 2007). Moreover, higher adjustment costs can lead to slower and weaker responses to shocks, as being able to quickly adjust investment is key to taking advantage of economic changes (Torres, 2020). If adjustments are too slow, the economy might miss out on growth opportunities and recover more slowly from shocks (Christiano et al., 2005). Therefore, investment adjustment costs play a substantial role in accounting for various macroeconomic dynamics (Groth and Khan, 2010).

The structure of the thesis is organised as follows. Section 2 presents a comprehensive literature review, which outlines the three DSGE models, highlighting their implications and theoretical differences. Section 3 describes the methodology employed, explaining the research design and its components. Section 4 encompasses the simulation analysis which is divided into two parts: the impulse response function analysis and the consecutive sensitivity analysis. In Section 5, the results are discussed and put into context, together with the limitations of the study. Finally, Section 6 concludes. Additional figures are available in the appendix for further reference.

2 Literature Review

This literature review provides a comprehensive description of the three models, highlighting their structural differences and implications for economic dynamics. The review begins with an examination of the baseline DSGE model developed by Smets and Wouters (2007), which integrates various real and nominal rigidities. It then moves to the model by Christiano et al. (2016), which introduces labour market frictions through search and matching mechanisms and provides a detailed perspective on wage dynamics. Finally, the model of Christiano et al. (2014) is examined, which introduces a financial accelerator mechanism to provide insights into the role of credit market imperfections in business cycle fluctuations. This comparison sheds light on the different underlying dynamics of the models, setting the stage for a more detailed investigation in the following sections.

2.1 Smets and Wouters (2007)

In order to compare the three models in a legitimate way, it is important to state the differences between a standard Dynamic Stochastic General Equilibrium (DSGE) model and a model that includes labour market or financial frictions. The model of Smets and Wouters (2007) serves as a baseline for comparison here, as it includes not only a number of real and nominal frictions, but also several structural shocks to seven macroeconomic variables (Justiniano et al., 2010; Smets and Wouters, 2007). The framework of this model is based on the well-known models of Christiano et al. (2005), Smets and Wouters (2003) and Smets and Wouters (2005). However, SW features a deterministic growth rate driven by labour-augmenting technological progress and a Kimball (1995) aggregator in the goods and labour markets instead of the Dixit and Stiglitz (1977) technology (Smets and Wouters, 2007). This has certain implications, such as a time-varying, and therefore non-constant elasticity of substitution between goods. It also leads to a dependence on their relative price and allows for a more realistic degree of price and wage stickiness, which is relevant for the following research purposes (Harding et al., 2022).

Households choose the optimal amount of consumption, hours worked, bonds purchased, investment and capital utilisation to maximise, subject to a utility function denoted by

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

with regard to an intertemporal budget constraint

$$\begin{aligned} & C_{t+s}(j) + I_{t+s}(j) + \frac{B_{t+s}(j)}{\varepsilon_t^b R_{t+s} P_{t+s}} - T_{t+s} \\ & \leq \frac{B_{t+s-1}(j)}{P_{t+s}} + \frac{W_{t+s}^h(j) L_{t+s}(j)}{P_{t+s}} + \frac{R_{t+s}^k Z_{t+s}(j) K_{t+s-1}(j)}{P_{t+s}} - a(Z_{t+s}(j)) K_{t+s-1}(j) + \frac{Div_{t+s}}{P_{t+s}} \end{aligned} \tag{2}$$

There is external habit formation included to enhance the persistence of the consumption response in the model (Smets and Wouters, 2007). Further, consumption depends also on expected growth in labour input and allows for intertemporal substitution between consumption and hours worked (Smets and Wouters, 2007). Following Smets and Wouters (2007), households rent capital services to firms and choose, based on capital adjustment costs, the amount of capital to accumulate. Furthermore, households' financial wealth has the form of state-contingent bonds which they hold for one period. The accumulation of installed capital is given by

$$K_t(j) = (1-\delta) K_{t-1}(j) + \varepsilon_t^i \left[1 - S\left(\frac{I_t(j)}{I_{t-1}(j)} \right) \right] I_t(j), \tag{3}$$

where $S(\cdot)$ is the adjustment cost function. Capital accumulation depends on the one hand on the investment flow and on the other hand on the efficiency of investment expenditures which is given by the investment-specific technology shock:

$$\ln \varepsilon_t^i = \rho_i \ln \varepsilon_{t-1}^i + \eta_t^i \tag{4}$$

This disturbance is to be investigated in the following analysis and affects both capital and investment responses. Investment is determined by the investment Euler equation which includes the steady-state elasticity of the capital adjustment cost function (Smets and Wouters, 2007). Similar to Christiano et al. (2005), a higher elasticity of capital adjustment costs leads to a lower sensitivity of investment to the real value of the existing capital stock (Smets and Wouters, 2007). With capital adjustment costs modelled as a function of changes in investment instead of its level, it is more straightforward to capture the hump-shaped responses of investment (Smets and Wouters, 2007). Ultimately, households decide on the utilisation rate of capital. The amount of effective capital rented to the firms is:

$$K_t^s(j) = Z_t(j) K_{t-1}(j). \tag{5}$$

According to Smets and Wouters (2007), capital is composed by capital accumulated in the previous period and a capacity utilisation variable which reflects costs occurring when adjusting the amount of capital. This variable is linked to the rental rate of capital and depends on the elasticity of the capital utilisation adjustment cost function.

On the supply side, the aggregate production function is given by

$$Y_t(i) = \varepsilon_t^a K_t^s(i)^\alpha \left[\gamma^t L_t(i)\right]^{1-\alpha} - \gamma^t \Phi, \tag{6}$$

using labour and capital inputs to produce output subject to fixed costs and a shock to total factor productivity, where

$$\ln \varepsilon_t^a = (1-\rho_z)\ln \varepsilon^a + \rho_z \ln \varepsilon_{t-1}^a + \eta_t^a. \tag{7}$$

The price mark-up is defined by the difference between the real wage and the marginal product of labour which itself is determined by the capital-labour ratio and the effects of the productivity shock (Smets and Wouters, 2007). Prices are assumed to be in accordance to the Calvo (1983) framework meaning that only a fraction of firms can adjust their prices optimally (Romer, 2018). The aggregate price index is given by:

$$P_t = (1-\xi_p)P_t(i)G'^{-1}\left[\frac{P_t(i)\tau_t}{P_t}\right] + \xi_p\left(\pi_t^{\lambda_p}\pi_{t-1}^{1-\lambda_p}\pi_*^{1-\lambda_p}P_{t-1}G'^{-1}\right)\left[\frac{\pi_t^{\lambda_p}\pi_{t-1}^{1-\lambda_p}P_{t-1}\tau_t}{P_t}\right]. \tag{8}$$

The beliefs regarding price stickiness ξ_p are broadened such that prices that can not be reoptimised are partially indexed to previous inflation rates, leading to a gradual adjustment to the favored mark-up (Smets and Wouters, 2007). Price inflation is then determined by the New-Keynesian Phillips curve. As stated in Smets and Wouters (2007), inflation is positively affected by past and expected future inflation and by a mark-up shock. However, it is negatively related to the current price mark-up. Furthermore, the speed of adjustment to the desired mark-up includes the degree of price stickiness, the curvature of the Kimball goods market aggregator and the steady-state mark-up, which is linked to the share of fixed costs of production (Smets and Wouters, 2007). A higher curvature increases strategic complementarity and slows down the speed of adjustment (Harding et al., 2022). Similarly, a higher degree of price stickiness leads to slower adjustment (Henkel, 2020).

Labor is differentiated through a union which grants some monopoly power over wages and leads to the formulation of an explicit wage equation:

$$W_t = \left[(1-\zeta_w)\widetilde{W}_t^{\frac{1}{\lambda_{w,t}}} + \zeta_w \left(\gamma_t \pi_t^{\lambda_w} \pi_{t-1}^{1-\lambda_w} \pi_*^{1-\lambda_w} W_{t-1} \right)^{\frac{1}{\lambda_{w,t}}} \right] \lambda_{w,t} \tag{9}$$

Therefore, the real wage depends on a combination of expected and past real wages, anticipated, current, and previous inflation, as well as the wage mark-up and a wage mark-up disturbance (Smets and Wouters, 2007). Similar to prices, wage stickiness ξ_w à la Calvo (1983) is assumed. This characteristic, together with partial indexation, is one of the reasons why wages are slow to adjust to the desired mark-up (Smets and Wouters, 2007). In addition, the curvature of the Kimball labour market aggregator and the elasticity of demand for labour, which is influenced by the steady-state labour market mark-up, determine the speed of adjustment to the mark-up (Harding et al., 2022). The wage mark-up is defined as the difference between the real wage and the marginal rate of substitution between labour and consumption (Smets and Wouters, 2007). Finally, regarding monetary policy, the Smets and Wouters (2007) rule is a well-know rule among medium-scale New Keynesian (NK) models (Wieland et al., 2016, 2012). The model implements a generalised Taylor (1993) rule where short-term interest rates are set according to

$$\frac{R_t}{R^*} = \left(\frac{R_{t-1}}{R^*}\right)^{\rho_R} \left[\left(\frac{\pi_t}{\pi^*}\right)^{\psi_1} \left(\frac{Y_t}{Y_t^*}\right)^{\psi_2} \right]^{1-\rho_R} \left(\frac{Y_t/Y_{t-1}}{Y_t^*/Y_{t-1}^*}\right)^{\psi_3} r_t \tag{10}$$

with a shock to monetary policy, given by

$$\ln r_t = \rho_r \ln r_{t-1} + \varepsilon_{r,t}. \tag{11}$$

The policy rule includes a lagged interest rate while trying to adjust to a target which depends on the inflation rate, the output gap and its corresponding growth rate.

The SW model has without doubt a great potential for modelling a robust economy, as it implements various shocks and frictions such as adjustment costs, capacity utilisation costs, habit persistence, and price and wage stickiness (Smets and Wouters, 2007). Moreover, the indexation of prices and wages helps to match inflation persistence, which previous NK models failed to reproduce (Dixon and Kara, 2006). However, there is still a need for further development, as standard models have notable limitations, especially when labour market and financial dynamics are taken into account. For example, one of the weaknesses of these models is their minimal focus on financial frictions, a limitation that has a significant impact on the accuracy of these models. Furthermore, standard DSGE frameworks mostly do not take into account wage inertia, and the sluggish response of wages to economic changes (Christiano et al., 2016), they simply model wages as exogenously sticky (Christiano et al., 2005; Galí et al., 2012; Smets and Wouters, 2007). In sum, limitations such as these suggest the need to take a closer look at models that incorporate labour market frictions in order to provide a more insightful analysis of the economy, such as a search and matching model like that of Christiano et al. (2016).

2.2 Christiano et al. (2016)

To gain a broader perspective in this comparative analysis, the work of Christiano et al. (2016) is considered. The model incorporates search and matching frictions into a standard NK framework and examines the dynamics of various macroeconomic aggregates when wages are derived through firm-worker negotiations. The model follows the approach of Hall and Milgrom (2008), which uses bargaining with alternating offers to determine the real wage. It addresses the fact that, in a standard framework, wages tend to rise too quickly, leading to a larger increase in inflation, in response to an expansionary monetary policy shock (Christiano et al., 2016). Besides, in a real-world economy, workers would not rely on wages that are subject to the nominal frictions imposed by the modellers. This is contrary to the standard assumption that wages are affected by exogenous nominal frictions, as in Smets and Wouters (2007) or Christiano et al. (2005). Further, wages are also partially indexed to inflation in the model of SW, although there is weak empirical evidence supporting this assumption (Christiano et al., 2016; Taylor, 2016).

On the demand side of the model, households maximise consumption including habit formation, given by

$$E_0 \sum_{t=0}^{\infty} \beta^t \ln(C_t - bC_{t-1}) \tag{12}$$

while being subject to a budget constraint:

$$P_t C_t + P_{I,t} I_t + B_{t+1} \leq \left(R_{K,t} u_t^K - a(u_t^K) P_{I,t}\right) K_t + (1 - l_t) P_t D_t + W_t l_t + R_{t-1} B_t - T_t. \tag{13}$$

The left side of the budget constraint describes the costs of consumption and investment as well as the purchase of the one period risk-free bonds. On the right side, household's total income and returns are represented. This includes the income from renting out capital services, where u_t^K is the capital utilisation rate. This income is adjusted by subtracting the cost of capital utilisation, where $a(u_t^K)$ denotes the cost of capital utilisation in terms of investment goods. The right-hand side shows labour income and unemployment compensations by the government. The household also receives income from holding one-period risk-free bonds purchased in the previous period. Finally, lump sum taxes net of profits are subtracted.

The households rent capital services to firms and make a decision on the amount of capital to accumulate, which is given by

$$K_{t+1} = (1 - \delta_K) K_t + \left[1 - S\left(\frac{I_t}{I_{t-1}}\right)\right] I_t, \tag{14}$$

constrained by the following investment adjustment cost function:

$$S\left(\frac{I_t}{I_{t-1}}\right) = \frac{1}{2}\left(\exp\left[\sqrt{S''}\left(\frac{I_t}{I_{t-1}} - \mu \times \mu_\Psi\right)\right] + \exp\left[-\sqrt{S''}\left(\frac{I_t}{I_{t-1}} - \mu \times \mu_\Psi\right)\right]\right) - 1. \tag{15}$$

The second derivative of $S(\cdot)$, S'', marks the investment adjustment costs as in the model of SW. Facing the supply side, the final goods sector produces a homogeneous good under perfect competition using a Dixit and Stiglitz (1977) technology assuming constant elasticity of substitution, instead of a Kimball (1995) aggregator as in the model of SW:

$$Y_t = \left[\int_0^1 (Y_{j,t})^{1/\lambda} \, dj\right]^\lambda. \tag{16}$$

The resulting good can be used as an input for the production of either consumption or investment goods (Christiano et al., 2016). The latter is defined by a linear technology where one unit of the final good is transformed into Ψ_t units of investment goods (Christiano et al., 2016). The investment-specific technology shock evolution is given by

$$\Psi_t = (1 - \rho_\Psi)\Psi + \rho_\Psi \Psi_{t-1} + \sigma_\Psi \varepsilon_{\Psi,t}. \tag{17}$$

A monopolistic retailer produces the input good needed by the final good producer by acquiring capital services and producing subject to fixed costs:

$$Y_{j,t} = k_{j,t}^\alpha \left(z_t h_{j,t}\right)^{1-\alpha} - \phi_t. \tag{18}$$

The neutral technology shock is denoted by

$$z_t = (1 - \rho_z)z + \rho_z z_{t-1} + \sigma_z \varepsilon_{z,t}, \tag{19}$$

and mirrors the neutral technology shock in SW, both being studied in the following analysis. Following Christiano et al. (2016), the retailer buys intermediate goods from a wholesaler in a competitive market by borrowing the amount of capital needed at the gross nominal interest rate. This loan is repaid at the end of each period after receiving the sales profits. As in SW, the retailers set prices subject to the Calvo (1983) sticky price framework where only a fraction of retailers can reset their prices. The remaining fraction which can not reoptimise their prices are not allowed to index prices to inflation, leaving the majority of prices unchanged for multiple periods (Eichenbaum et al., 2011; Klenow and Malin, 2010).

Wholesalers hire workers in the labour market and produce the intermediate good by using labour input which has a constant marginal productivity of one (Christiano et al., 2016). After Christiano et al. (2016) the dynamics of the labour market are as follows. Each one of the numerous identical households has a dedicated fraction of employed workers supplying labour and earning income at a nominal wage rate. A firm that wants to meet a worker has to post a costly vacancy which is expressed in units of consumption. There is a given probability that the vacancy is filled, if that is the case then the firm has to pay a fixed cost before the bargaining process with the new worker initiates. Worker and firm then engage in bilateral bargaining. If both parties agree, the production starts promptly. Further, there is a specific probability that the job agreement continues in the following period.

The special feature of this model marks the fact that wages are derived by a bargaining process, thus, as an equilibrium outcome. The model of Christiano et al. (2016) features two versions of bargaining, the alternating offer bargaining which is a modified version of Hall and Milgrom (2008) and Nash bargaining. However, the former is a much better fit since it does not require implausibly high replacement ratios to match the data (Christiano et al., 2016). As a result, the alternating offer bargaining is considered as the framework of choice and is explained as follows. It consists of a sequence of offers and, in the event of rejection, counter-offers. The basic implication is that workers and firms believe that reaching an agreement is a better outcome than parting without an agreement. The two agents bargain over the current wage and take the outcome of future bargaining as given. The mechanism as such takes place between workers and firms who have just met for the first time, as well as between those who have reached an agreement in the previous period, which still exists. The company starts with an initial offer, and if the worker rejects it, it makes a counter-offer. This back and forth continues until an agreement is reached. If no agreement is reached by the final stage, the worker makes a take-it-or-leave-it offer. If either party accepts an offer at any point, production begins immediately.

In terms of monetary policy, the model implements an advanced Taylor (1993) type rule that includes interest rate smoothing and captures responses to deviations from the inflation target as well as to changes in the output gap (Christiano et al., 2016). Additionally, the monetary policy rule is affected by a corresponding shock, which completes the equation, given by

$$\ln\left(\frac{R_t}{R}\right) = \rho_R \ln\left(\frac{R_{t-1}}{R}\right) + (1-\rho_R)\left[r_\pi \ln\left(\frac{\pi_t}{\bar{\pi}}\right) + r_y \ln\left(\frac{Y_t}{Y_t^*}\right)\right] + \sigma_R \varepsilon_{R,t}, \tag{20}$$

with $\varepsilon_{R,t}$ denoting a shock to monetary policy.

Overall, the CET model captures the same frictions as a standard NK model, such as that of SW, by including habit formation, capital utilisation, investment adjustment costs and price stickiness (Christiano et al., 2016; Smets and Wouters, 2007). However, in sharp contrast to the baseline model, there is no underlying assumption of wage stickiness as described in Calvo (1983). In particular, the wage equation is an equilibrium result, more precisely the result of bilateral bargaining between firms and workers (Christiano et al., 2016). Furthermore, there is no indexation of prices or wages (Christiano et al., 2016). Therefore, the model is able to capture key features of real wages that together characterise wage inertia. With respect to Christiano et al. (2016), the key results show that inflation has a relatively small response to a monetary policy shock. It follows that the shock leads to a small response in firms' marginal costs. This implies that wages are inertial. In addition, a positive neutral technology shock leads to a large reduction in inflation and hence in marginal costs. Here, wage inertia prevents a significant increase in the real wage, which would otherwise neutralise this fall in inflation. In order to gain a full understanding of the economic dynamics at play, it is essential to also examine a model that incorporates financial frictions. The next section reviews a model that takes these frictions into account, providing a more complete picture of the economic mechanisms at play.

2.3 Christiano et al. (2014)

The framework of Christiano et al. (2014) introduces a financial accelerator mechanism as in Bernanke et al. (1999) into an otherwise standard DSGE model as in Smets and Wouters (2007) or Christiano et al. (2005). The present model implements external financial frictions, such as agency problems associated with the burden of asymmetric information and monitoring costs (Townsend, 1979). In addition, the process of capital transformation is assumed to be affected by a time-varying cross-sectional standard deviation of an idiosyncratic productivity shock. This type of shock, called a risk shock, follows the model described by Christiano et al. (2004).

Looking at aggregate demand, households are assumed to follow the large family assumption of Andolfatto (1996) and Merz (1995). Every household has each type of differentiated labour as well as a large amount of entrepreneurs which will be in focus in a following paragraph (Christiano et al., 2014). They maximise the utility function, consisting of consumption and labour services, given by

$$E_0 \sum_{t=0}^{\infty} \beta^t \zeta_{c,t} \left\{ \log(C_t - bC_{t-1}) - \psi_L \int_0^1 \frac{h_{it}^{1+\sigma_L}}{1+\sigma_L} \, di \right\}, \tag{21}$$

while being subject to a budget constraint:

$$\begin{aligned} &(1+\tau^c)P_t C_t + B_{t+1} + B_{t+40}^L + \left(\frac{P_t}{\Upsilon_t \mu_{\Upsilon,t}}\right) I_t + Q_{K,t}(1-\delta)\bar{K}_t \\ &\leq (1-\tau^l) \int_0^1 W_t^i h_{i,t} \, di + R_t B_t + (R_t^L)^{40} B_t^L + Q_{K,t}\bar{K}_{t+1} + \Pi_t. \end{aligned} \tag{22}$$

Again, habit formation in consumption is included. Following Christiano et al. (2014), funds are acquired by earning income from labour services, the returns on short- and long-term bonds, profits of capital sold and various lump-sum payments. These payments consist of revenues from intermediate goods, money transfers from entrepreneurs and lump-sum transfers from the government revenue remaining after lump-sum taxes. On the other side of the budget constraint, households allocate resources to consumption, the two types of bonds, existing capital and investment.

Households build and sell raw capital by purchasing existing capital and investment goods, according to

$$\bar{K}_{t+1} = (1-\delta)\,\bar{K}_t + \left(1 - S\left(\zeta_{I,t}\frac{I_t}{I_{t-1}}\right)\right) I_t \tag{23}$$

with

$$S(x_t) = \frac{1}{2}\left\{\exp\left[\sqrt{S''}(x_t - x)\right] + \exp\left[-\sqrt{S''}(x_t - x)\right]\right\} - 2. \tag{24}$$

As in CET and SW, S'' is the parameter characterising the investment adjustment costs, the parameterisations and effects of which are examined in the sensitivity analysis.

Further, in terms of aggregate supply, a competitive final goods producer uses a Dixit-Stiglitz

(1977) function to produce a homogeneous good by combining intermediate goods, equal to the one of CET (Equation 16). Intermediate goods are produced by a monopolistic retailer which uses hired labour services and rented effective capital as input factors, while being affected by fixed production costs:

$$Y_{jt} = \varepsilon_t K_{jt}^{\alpha} (z_t l_{jt})^{1-\alpha} - \Phi z_t^*. \tag{25}$$

In this equation, ε_t denotes a technology shock that is examined in the analysis together with the other two shocks in SW and CET that represent the same type of disturbance.

The monopolists determines prices subject to Calvo (1983)-style rigidities. In line with SW and contrary to CET the firms which can not reoptimise their prices index them to previous inflation rate (Christiano et al., 2014).

Similar to CET, there is a technology which transforms homogeneous goods into $\Upsilon^t \mu_{\Upsilon,t}$ units of investment goods, with $\mu_{\Upsilon,t}$ being a shock to this investment-specific technology (Christiano et al., 2014). This disturbance is examined in more detail in the following analysis, together with the respective shocks in CET and SW.

Turning to the labour market of the model, adopted from Erceg et al. (2000), a perfectly competitive labour contractor uses the Dixit-Stiglitz technology to produce a homogeneous labour good:

$$l_t = \left[\int_0^1 (h_{t,i})^{\frac{1}{\lambda_w}} \, di \right]^{\lambda_w}. \tag{26}$$

Inputs are differentiated labour services supplied by households which are bought from monopolistic unions that represent each type of labour and set the corresponding wage rate according to the Calvo (1983)-framework as well (Christiano et al., 2014). In addition, for the remaining subset of monopoly unions which can not reoptimise their wages, they are partially indexed to past inflation rates as well, echoing the price mechanism (Christiano et al., 2014). Further, the labour contractor then proceeds to sell the labour good to the intermediate goods sector at a nominal wage rate (Christiano et al., 2014).

Regarding the distinctive part of this model, compared to a standard DSGE model, the financial sector of Christiano et al. (2014) is described. Households build raw capital and sell it to risk-neutral entrepreneurs. Entrepreneurs can be interpreted as banks, which now step in between the borrowing process of capital, which normally only takes place between households and firms. This creates agency problems due to asymmetric information about the return on capital. Entrepreneurs are characterised by their net worth and use it, together with loans from households, to transform raw capital into effective capital. Furthermore, this mechanism is defined by idiosyncratic uncertainty, referred to as risk, which is affected by a shock that affects the entrepreneur's return on capital. The entrepreneur generates income from selling capital and from capital gains, after which he repays his loan and transfers funds between his household and himself. Moreover, the loan contract of Bernanke et al. (1999) is used between entrepreneurs and households, which are the ultimate source of funds. Thus, with the agency problem that arises between the two contracting parties, a risk shock raises the required rate of return on borrowing, namely the external finance premium. As mentioned above, an important component of this financial friction model is the loan contracts between entrepreneurs and investment funds. The interest rate on loans to entrepreneurs includes a premium to cover the risk of default by entrepreneurs who have little success in transforming capital. Moreover, the credit spread, i.e. the difference between the entrepreneur's interest rate and the risk-free rate, varies with fluctuations in risk, which is the result of a stochastic process. Therefore, when the level of risk is high, the credit spread is wide and the amount of credit available to entrepreneurs decreases.

The monetary authority's policy rule is a representation of a Taylor (1993) type rule, where the interest rate is set based on the deviations of inflation and output from their respective targets, along with a degree of interest rate smoothing. A shock to monetary policy is also implemented, resulting in:

$$R_t - R = \rho_p(R_{t-1} - R) + (1 - \rho_p)\left[\alpha_\pi(\pi_{t+1} - \pi_t^*) + \alpha_{\Delta y}\frac{1}{4}(g_{y,t} - \mu_z^*)\right] + \frac{1}{400}\varepsilon_t^p, \quad (27)$$

To clarify the differences between the CMR model and a stylised framework without financial frictions such as SW, it is necessary to drop the following equations describing imperfect financial markets (Christiano et al., 2014). First, the optimality condition that determines the contract chosen by entrepreneurs. Second, the equation that guarantees zero profits for financial intermediaries. Third, the law of motion for the net worth of entrepreneurs. In addition, it is crucial to remove banks' monitoring resources from the resource constraint equation and to introduce an intertemporal Euler equation for household capital accumulation. The CMR framework implements several features with respect to the financial sector that distinguish it from a standard DSGE model. The model assumes that the return on capital of individual entrepreneurs depends on idiosyncratic volatility, denoted as risk (Christiano et al., 2014). When a risk shock is introduced, it affects the variance of idiosyncratic productivity. This implies an increase in the required rate of return, the external finance premium, given the agency problem between entrepreneurs and financial providers (Christiano et al., 2014). The main result of (Christiano et al., 2014) is that such risk volatility is one of the most important drivers of the business cycle, especially for financial variables. A financial accelerator mechanism à la Bernanke et al. (1999) is included, explaining the role of credit market frictions and financial market imperfections on the economy. Moreover, similar to SW and CET, the model incorporates nominal and real frictions such as price and wage stickiness, partial indexation, habit formation and investment adjustment costs (Christiano et al., 2014). Nevertheless, the CMR model still has its caveats and limitations. For example, if the financial variables are not included, the risk shock loses much of its significance (Christiano et al., 2014). It is therefore necessary to examine how structural shocks and various frictions affect the accuracy of the models in reflecting economic dynamics. The next section explains the methodology used to study these differences in detail.

3 Methodology

The following section describes the methodology of the analysis carried out. First, the components of the analysis are described, including the models studied, the shocks implemented, the variables observed and the parameters varied. Next, the research design is explained, identifying the two parts of the analysis. The tools used for the analysis are also mentioned. Finally, the limitations of the methodology used are discussed.

The first model is a standard New Keynesian DSGE model developed by Smets and Wouters (2007) and serves as a baseline for comparison. The second model by Christiano et al. (2016) can be described as a NK model that includes search and matching frictions to account for a framework with more complex labour market dynamics. The third model of Christiano et al. (2014) embeds a Bernanke-Gertler-Gilchrist (1999) financial accelerator mechanism to represent a model with financial frictions. Together, these models allow for a more nuanced understanding of how labour and financial market frictions can affect macroeconomic outcomes. As mentioned above, the models are subject to three shocks that affect different parts of the economy, namely a monetary policy shock, a neutral technology shock and an investment-specific technology shock. By including a monetary policy shock in the analysis, it is possible to examine how the actions of a monetary authority, like changes in interest rates, affect key economic variables such as inflation, output and investment. In addition, the introduction of a neutral technology shock is essential to understand how changes in productivity can impact on an economy and its long-term growth. An investment-specific technology shock contributes to the analysis by illustrating the impact on business cycle fluctuations and economic growth. The shock sizes are normalised to one in all models, which facilitates the direct comparison of IRFs between models. In the CET model, the shock sizes are not initially set to one, but the standard deviation is estimated instead. Therefore the IRFs from CET are multiplied by 100 to ensure consistency with those in SW and

CMR.

The impact of the various shocks is illustrated by impulse response functions, which represent the dynamics of the model. To provide a more detailed insight, seven macroeconomic variables are analysed. They are output, consumption, investment, inflation, hours worked, real wages and interest rates. These key indicators are chosen because they appear in all three papers examined and capture the main characteristics of a model economy. The number of periods over which the IRFs are computed is set at 20, which is considered sufficient to capture the main dynamics of the model's response to the shocks, including both peak effects and subsequent convergence. The quantitative analysis is carried out using Dynare (Adjemian et al., 2024), implemented in MATLAB (The MathWorks Inc., 2023), which is used for economic modelling and simulation analysis. The main strength of Dynare lies in its ability to handle and solve DSGE models efficiently, making it suitable for studying the dynamic effects of the various shocks on the three models.

In order to make the models comparable, a number of transformations have to be made. First, since the SW model is log-linearised, it is necessary to ensure that the variables of the other models are also reported in log deviations from steady state. In the CET model, the reported equations are non-linear, but all variables are expressed in logs and transformed by applying an exponential function to each variable. *Dynare* then performs a linearisation which gives the log deviations (Pfeifer, 2014). The CMR model is also non-linear, so the log levels of the observed variables have to be defined as auxiliary variables. However, in this case the variables are given in levels, so the log of the steady states of the variables must be subtracted from the log of the variable to get them specified as percentage deviations from steady state.

The second part of the analysis is designed as a sensitivity analysis of the three models where the Calvo (1983) parameters governing price and wage stickiness, as well as the level of investment adjustment costs, are varied. These parameters are fundamental in capturing both nominal and real rigidities in the economy and allow an insight into how these frictions affect the responses of the models. Table 1 reports the posterior mode values of the model parameters studied in detail. The posterior mode is chosen to compare the parameterisation of the models because this point estimate is reported in all papers. It also combines prior beliefs with the empirical evidence provided by the observed data. This approach allows a reliable and robust comparison of parameter calibrations that reflect the underlying dynamics of the model. The SW model has

Table 1. Posterior Mode of Model Parameters. Values taken from Smets and Wouters (2007), Christiano et al. (2016) and Christiano et al. (2014).

Parameter	**SW (2007)**	**CET (2016)**	**CMR (2014)**
Calvo Price stickiness (ξ_p)	0.65	0.75	0.74
Calvo Wage stickiness (ξ_w)	0.73	–	0.81
Investment adjustment cost (S'')	5.48	15.70	10.78

the least sticky prices, indicating an average duration of price contracts of about three quarters (Smets and Wouters, 2007). In contrast, the CET model has the most sticky price calibration, implying a price change once every four quarters on average. The posterior mode of the CMR model also indicates a reasonable degree of price stickiness, as it is close to the point estimate of CET. Moreover, SW also has higher wage flexibility, suggesting that wages adjust less frequently in the CMR model. In addition, SW has the lowest investment adjustment costs, while CET has the highest, indicating slower investment responses (Torres, 2020). The CMR value for investment adjustment costs is in between the other two calibrations.

The quantitative part of the analysis first compares the impulse response functions of the different models under the same shocks to monetary policy, neutral technology and investment-specific technology. It therefore examines how the responses of the models to the main macroeconomic indicators differ when exposed to these shocks, while maintaining the initial parameterisation of each model. On the basis of the results obtained, a sensitivity analysis is carried out to further explore the differences between the models by varying the specified parameters and observing the impact on the dynamics of the models. The aim is to identify whether there are key parameters that mainly drive the responses of certain variables to a given shock. Overall, the approach described is appropriate for the purpose of the research, as it works out the differences between the models and their implications at both a theoretical and an analytical level. The methodology outlined provides a structured approach to compare the dynamic responses of the three models to different shocks. This lays the foundation for the next section, which discusses the results of the analysis and their implications.

4 Simulation Analysis Results

The first part of this chapter is devoted to analysing the responses of the three models to a either monetary policy, neutral technology or an investment-specific technology shock, given their initial parameter calibrations. Following this broad comparison, the second part focuses on a sensitivity analysis to gain insights into how the impulse response functions (IRFs) change when specific parameters such as price and wage stickiness and investment adjustment costs are varied in their calibration.

4.1 Impulse Response Function Analysis of the Models

4.1.1 Monetary Policy Shock

The IRFs to a monetary policy shock of the models SW, CET, and CMR are displayed in Figure 1. A first look reveals that the CET model shows a positive response to the monetary policy shock, whereas SW and CMR indicate a negative reaction. This is because CET implement an expansionary shock leading to a reduction in interest rates with the intention of stimulating the economy (Kim and Ruge-Murcia, 2011). Contrary, SW and CMR impose a contractionary monetary policy shock, which implies an increase in interest rates, leading to lower consumption and investment, and a decrease in inflation (Kim and Ruge-Murcia, 2011). The SW model shows similar responses for all macroeconomic variables. They react with a significant initial fall after the shock, but recover slowly over time. The interest rate shows an increase when the shock commences and then starts to fall before finally stabilising. This reflects the aggressive reaction of the central bank, trying to counter upcoming inflationary pressures, and then subsequently decreasing the instrument, coinciding with the gradual recovery of inflation (Smets and Wouters,

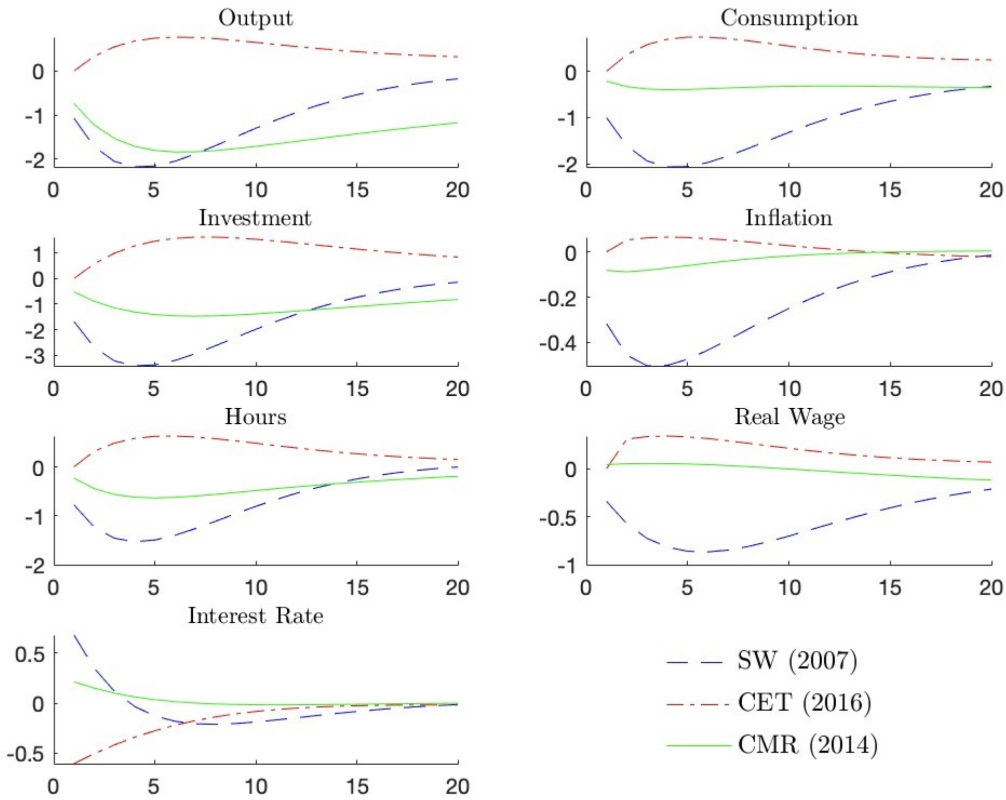

Figure 1. Model Comparison: Monetary policy shock. Blue, dotted line: (Smets and Wouters, 2007) (SW); Red, dash-dot line: (Christiano et al., 2016) (CET); Green, solid line: (Christiano et al., 2014) (CMR).

2007). In addition, it can be seen that the maximum impact of a monetary policy shock on inflation occurs earlier than its maximum impact on output (Smets and Wouters, 2007). Furthermore, Figure 2 depicts the variance decomposition for the three observed models. The monetary policy shock is the most important factor influencing the variations of interest rates and inflation, explaining over 74 % and 80 % of its fluctuations respectively. This is to be expected given that this shock directly targets interest rates. Additionally, the variance decomposition indicates that approximately 62 % of the variance in output and 73 % of variations in consumption are explained by the monetary policy shock.

A closer look at the model with included labour market frictions, CET, shows an opposite response to the framework of SW. The detailed results for this scenario are shown in Figure A.1.

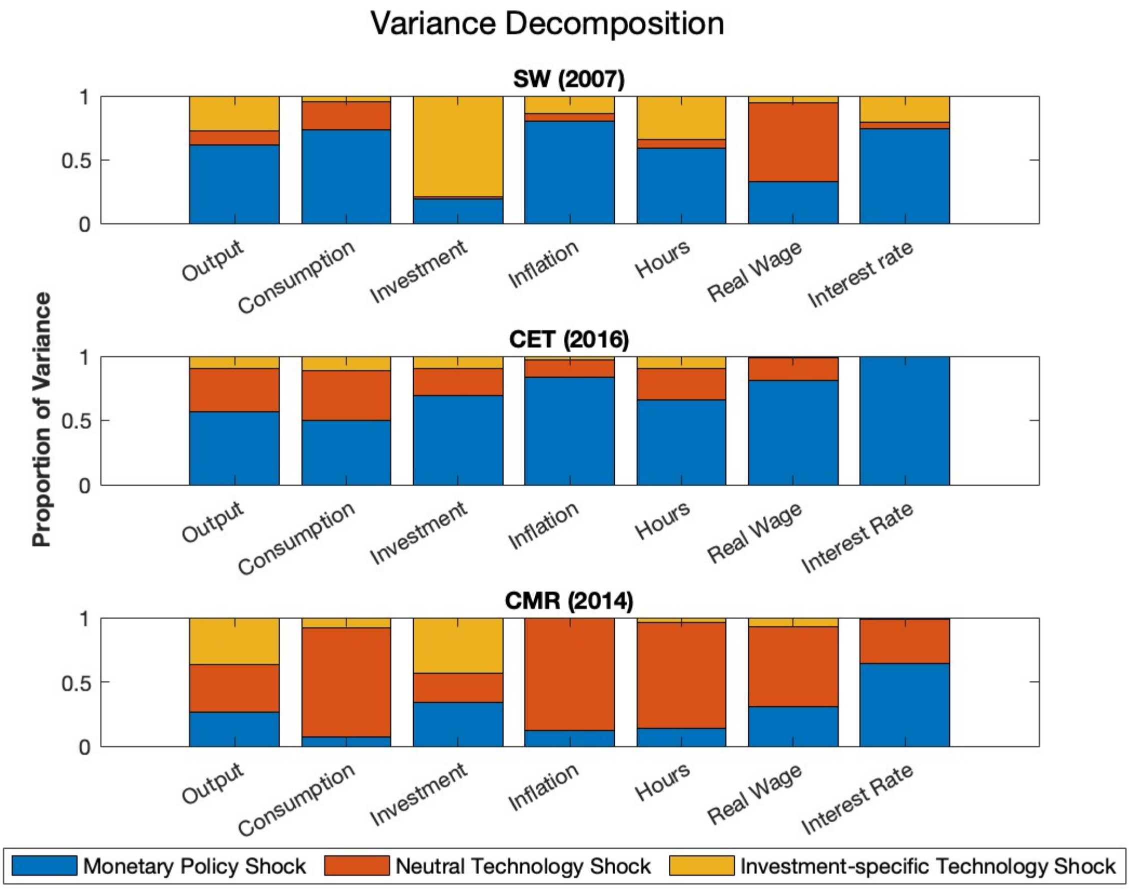

Figure 2. Variance Decomposition. Blue: Monetary Policy Shock; Red: Neutral Technology Shock; Yellow: Investment-specific Technology Shock.

That is, for each one of the variables, except the interest rate, declared as the federal funds rate in the paper (Christiano et al., 2016), the IRFs display a positively hump-shaped trajectory as a response to the policy shock. This is due to the fact that the model implements an expansionary monetary policy shock instead of a contractionary one. The dynamics of this disturbance can be explained as follows. In response to the above shock, the interest rate falls, boosting output by encouraging more spending and investment. The increased demand for final goods, and hence for the output of retailers, leads retailers to buy more wholesale goods (Christiano et al., 2016). This in turn raises the relative price of this good and the marginal revenue product associated with each worker. A higher marginal revenue product incentivises wholesalers to hire more workers and raises workers' disagreement payoffs, enhancing their bargaining power and finally leading to a rise in real wages and hours worked (Christiano et al., 2016). Consistent with the theoretical results, it can be observed that the alternating bargaining dynamics lead to a slight increase in real wages and inflation and, although not shown in the graph, to a substantial reduction in unemployment (Christiano et al., 2016). Further, as demand and investment rise, so does inflation. To combat this, a tightening monetary policy by the central bank leads to an increase in interest rates, which key macroeconomic indicators to fall. As an aside, it is assumed that the monetary authority observes the current values of the variables before changes to interest rates are made (Christiano et al., 2016). In addition, such a shock to monetary policy only has an immediate effect on the federal funds rate, while the other economic indicators react with a delay, making it possible to isolate the direct impact of the monetary policy decision (Christiano et al., 2016). Another factor influencing the fluctuations displayed is the habit parameter of CET with a posterior value of 0.80. This is in line with other NK DSGE models, such as the framework developed by Smets and Wouters (2007) which has a mode of 0.71. A value in this range is essential to replicate the gradual, hump-shaped rise in consumption following a monetary policy shock as displayed in Figure 1. Moreover, this explains the negative relation between the real interest rate and consumption in this period, since lower interest rates favour spending rather than saving (Christiano et al., 2016). Regarding the magnitude of the effect, real wages show a less pronounced response to this policy shock than hours worked. In addition, the response of inflation is noticeably smaller than that of the other macroeconomic variables. This is due to wage inertia, which is a key feature of the model (Christiano et al., 2016). The role of wage acyclicality in inflation dynamics is a central issue in the New Keynesian literature, as discussed in many papers such as Christiano et al. (2005). Inertial wages cause small changes in the marginal costs of firms, leading to a relatively small reaction of inflation to a monetary policy shock (Christiano et al., 2021). However, if real wages were to rise sharply and persistently, the model would counterfactually predict an unrealistically large increase in inflation (Christiano et al., 2016). Therefore, real wages play a huge part in the challenge of accurately reflecting the observed behavior of inflation in response to an expansionary monetary policy shock (Christiano et al., 2005). Furthermore, in the CET study, the monetary policy shock explains a substantial portion of the variance in interest rates and accounts for 84 % of the variance in inflation. In addition, 70 % of the variance in investment and 81 % of the variance in real wages is influenced by a shock to monetary policy compared to only 19 % and 32 % in the SW model.

Finally, the IRFs of the CMR model to a monetary policy shock resemble the SW model in most responses, apart from the real wage. See Figure A.2 for the detached response of the CMR model. As in the SW model, a contractionary shock to monetary policy is implemented, which initially causes interest rates to rise. In consequence, output, consumption, investment, inflation and hours worked show an initial decline after the shock, as shown in Figure 1. They continue to fall and eventually start to recover from their lows in the early periods. Similarly, inflation experiences a fall right when the shock hits the economy but soon starts to rise gradually after only a short time. This response mirrors the corresponding curve in the SW model, alongside with the response of the monetary authority, which reacts to the shock by initially lowering interest rates before slowly raising them as a delayed response to the recovery in inflation.

An interesting aspect of the CMR model is its response of the real wage to the monetary policy shock. After a slight but immediately positive impact, the real wage descends sharply, contrary to the results of SW. This could be due to a higher degree of Calvo (1983) wage stickiness ξ_w, with a posterior mode of 0.81 compared to 0.73 in the SW model. A higher value indicates less wage flexibility, meaning that fewer firms are able to adjust their wages optimally when the shock commences. As a result, wages do not adjust immediately and the reaction to shock is delayed.

Moreover, preceding literature has shown that the real interest rate is less responsive to shocks when prices and wages are sticky (Christiano et al., 2010b). This is confirmed by Figure 1 since the response for CMR is less pronounced to SW where wages and prices are more flexible. The variance decomposition reveals the fact that a notably smaller fraction of the variation in the key variables is explained by the monetary policy shock. This shock accounts for 64 % of the variance in the interest rate, making it the largest contributor, as in the SW and CET models. Nonetheless, its influence on inflation is not anywhere near as pronounced as for the other two frameworks.

4.1.2 Neutral Technology Shock

The second structural shock discussed is the neutral technology shock. A shock to technology, labelled in the model of SW as a total factor productivity shock, is an impact on the supply-side and has considerable effects on the economy (Gelain et al., 2010). The impulse response functions of SW, displayed in Figure 3, show a positive and steady evolution for the macroeconomic variables output, consumption, investment as well as real wage. The trajectories of these variables depict a substantial increase immediately after the shock commences, in line with an increased level of productivity boosting the economy at large (Smets and Wouters, 2007). Besides the expansions of many indicators, a positive shock to productivity leads to a prompt and substantial short-run decrease in hours worked which does not return to pre-shock levels sooner than two years after the shock. A positive productivity shock causes an instantaneous drop in hours worked due to nominal price rigidities, habit formation in consumption and investment adjustment costs (Francis and Ramey, 2005; Gali, 1999; Galí and Rabanal, 2004). In addition, increased habit formation causes consumers to maintain a smooth consumption stream instead of increasing labour supply (Kano and Nason, 2014). Also, with a high level of capital adjustment costs firms can not adjust as quickly to a rising demand of labour due to elevated productivity which leads

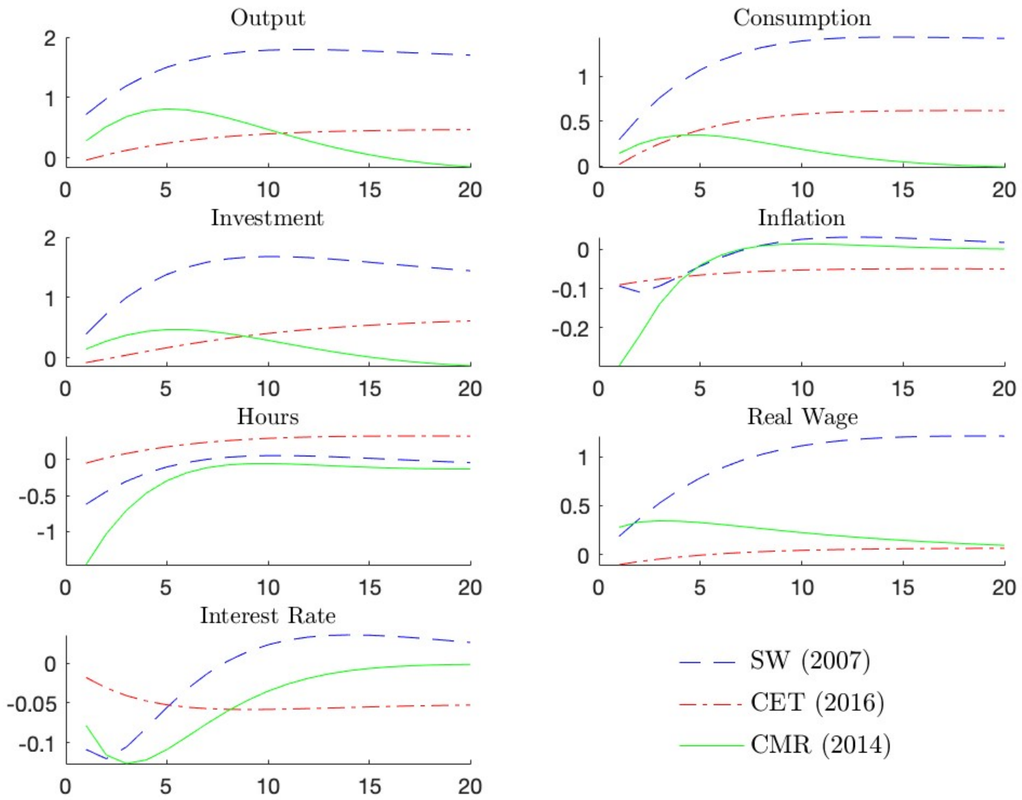

Figure 3. Model Comparison: Neutral Technology Shock. Blue, dotted line: (Smets and Wouters, 2007) (SW); Red, dash-dot line: (Christiano et al., 2016) (CET); Green, solid line: (Christiano et al., 2014) (CMR).

then to a lower amount of hours worked in the short term (Groth and Khan, 2010). According to Smets and Wouters (2007), the small and short-lived increase in hours worked in the medium term is due to the temporary nature of the productivity shock, which causes output to return to its baseline just as the effects on hours worked begin to take hold (Smets and Wouters, 2007). Additionally, a positive shock to productivity lowers the fixed costs per production unit which leads to a lower amount of labour required to produce a given level of output (Smets and Wouters, 2007).

A decrease in interest rates is observed in response to the technology shocks. However, they do not decrease sufficiently to hinder a consequential drop of inflation rate which stabilises towards zero over time together with the interest rate. The modest effect of productivity shocks on inflation dynamics can be explained by two factors. On the one hand, due to the small slope of the New Keynesian Phillips curve, inflation does not respond strongly to changes in marginal costs unless they are significant and sustained (Smets and Wouters, 2007). Although, more substantially, the proactive monetary policy response to output gaps and inflation risks ensures any inflationary pressures are quickly mitigated through interest rate adjustments (Smets and Wouters, 2007). This keeps inflation stable despite the presence of these shocks.

Furthermore, in Figure 2 it becomes apparent that a shock to neutral technology has a small impact on inflation fluctuations, explaining less than 7 % of its variance. On the other hand, the results show a dominance of neutral technology shock shocks, which account for 62 % of the variance in real wages, indicating that supply-side factors are powerful in driving wage fluctuations.

Turning towards the model augmented by search and matching frictions, CET, the impacts of a neutral technology shock are also depicted in Figure 3. The isolated responses of this model can be found in Figure A.3. Similar to the SW model, the CET framework exhibits a positive response in almost all variables observed, even though there is an initial fall in inflation, real wage and the interest rate. The macroeconomic variables output, consumption, investment and hours worked show a steady increase throughout, where the investment response displays a more steep trajectory compared to the other indicators. A modest fall in the inflation rate can be observed as the shock commences. This is because an increase in the level of technology reduces marginal costs and thus inflation (Ireland, 2004). However, the response of inflation is muted throughout the implemented shocks, especially in comparison to the models of SW and CMR. Similarly to the monetary policy shock analysis, wage inertia is repeatedly a significant factor that hinders a considerable rise in real wages, which would otherwise counteract this downward pressure on inflation (Christiano et al., 2016). Moreover, Christiano et al. (2016) find that in a model with sticky wages, here SW and CMR, the inflation response is understated, which can be confirmed due to the quick recovery of the initial fall of the two models. It is also noteworthy that the inflation response is more pronounced if affected by a shock to technology compared to a monetary policy shock, being in accordance with Paciello (2011).

Furthermore, the IRF drop of hours worked is much smaller in magnitude compared to the reaction in SW and CMR. Although it has previously been argued that a positive productivity shock results in a reduction in the amount of labour (Smets and Wouters, 2007), it has been proposed that the negative impact of a productivity shock on hours worked is not particularly robust and could be compatible with a positive effect on hours worked (Christiano et al., 2003; Dedola and Neri, 2007; Peersman and Straub, 2009). Additionally, Smets and Wouters (2007) state that more flexible prices lead to a notable reduction in the number of hours worked, which is validated by the higher Calvo (1983) price parameter of CET being 0.75 instead of the SW value of 0.65. As shown in Figure 2, neutral technology shocks explain about a third of the variance in output and 38 % of the variation in consumption, implying that supply-side shocks play an important role in firm- and household-specific decisions.

The next section will discuss the impact of a neutral technology shock to the model with financial frictions, CMR. In contrast to SW and CET, the IRFs of the CMR framework generally exhibits more hump-shaped responses to a neutral technology shock which can be observed in more detail in Figure A.4. This indicates a less persistent and thus stronger decline especially in output, consumption, real wage and investment responses. In CMR the effects of the shock build up more gradually before peaking and then slowly decrease over time. This dampening effects on long-term responses might be attributed to more rigidities in prices and wages, reflected by the Calvo (1983) parameters ξ_p with a value of 0.74 as well as ξ_w of 0.81 (Christiano et al., 2014). The values of the SW model are 0.65 and 0.73, respectively, leading to a faster and more pronounced reaction to structural changes (Christiano et al., 2014; Henkel, 2020; Smets and Wouters, 2007). The same reasoning can be applied to lower investment adjustment costs S'', where the CMR parameterisation of 10.78 contrasts with SW of 5.48 (Christiano et al., 2014; Smets and Wouters, 2007). Furthermore, the shock analysed is implemented as a so-called transitory technology shock which implies a temporary and diminishing effect over time (Christiano et al., 2014). As stated above, inflation displays a more pronounced response to technology shocks than a shock to monetary policy (Paciello, 2011). To be more specific, it appears that the inflation rate as well as hours worked drop by a strikingly higher amount than in the SW and CET model. The more pronounced negative response of the number of hours worked could also be explained by higher nominal rigidities and adjustment costs (Smets and Wouters, 2007). Moreover, real wages undergo an increase as the shock commences but suddenly start to decline rather early, in contrast to the SW and CET models, in which real wages increase steadily. A modest effect on interest rate is observed in response to a neutral technology shock in the CMR model. The initial fall is less pronounced than in the SW model, followed by a smaller subsequent increase, which eventually approaches a value close to zero. The shock to neutral technology is the most important driver of most of the observed variables. It accounts for approximately 80 % of the variance in consumption and hours worked as well as for 62 % of the variation in real wage. While a monetary policy shock explains only around 12 % of the fluctuations in the inflation rate, the neutral technology shock accounts for 87 %, suggesting that changes in technology have a great influence in this model.

In summary, the three models show an overall positive response of macroeconomic variables such as output, consumption and investment to a technology shock. However, it is clear that the CMR model lacks long-run effects, demonstrating the transitory nature of the productivity shock (Smets and Wouters, 2007). Apart from the negative effects on inflation and hours worked, the SW framework shows a stronger impact of the shock. In the CET model, the decline in hours worked is less dramatic than in the other two, suggesting that the negative impact of a productivity shock on labour may not be as robust and even be positive in some cases (Christiano et al., 2003; Dedola and Neri, 2007; Peersman and Straub, 2009). Real wages initially rise in the CMR model, but then fall earlier than in the other models. Wage inertia and high adjustment costs further dampen the response of hours worked and inflation in CET (Christiano et al., 2016). Also, in SW, inflation is kept relatively stable due to the small slope of the NK Phillips curve and the proactive monetary policy (Smets and Wouters, 2007).

4.1.3 Investment-specific Technology Shock

The last structural shock observed, identified as an investment-specific technology shock in the study of SW, impacts the inter-temporal margin of the economy. The impulse response functions of the SW model in Figure 4 exhibit not only strong but also immediate, mostly hump-shaped, responses to the above-mentioned disturbance. The model captures highly positive effects on the economy and its key indicators, with strong initial increases followed by a gradual decline or, as in the case of consumption, stabilisation. The different trajectory of the consumption response can be explained by intertemporal substitution decisions, consumption smoothing and the immediate reaction of the central bank, which decides to raise interest rates until inflation stabilises (Hall, 1988). Further, the investment-specific technology shock can be characterised as a demand shock, meaning that it has a clearly positive impact on output, consumption, investment, hours worked and real wages (Justiniano et al., 2010; Smets and Wouters, 2007). Hours worked and real wages both rise, reflecting an increase in labour demand as firms expand production in response to the shock (Asamoah, 2021). The interest rate, together with inflation, increases slightly initially, as the central bank reacts to the heightened economic activity and inflationary

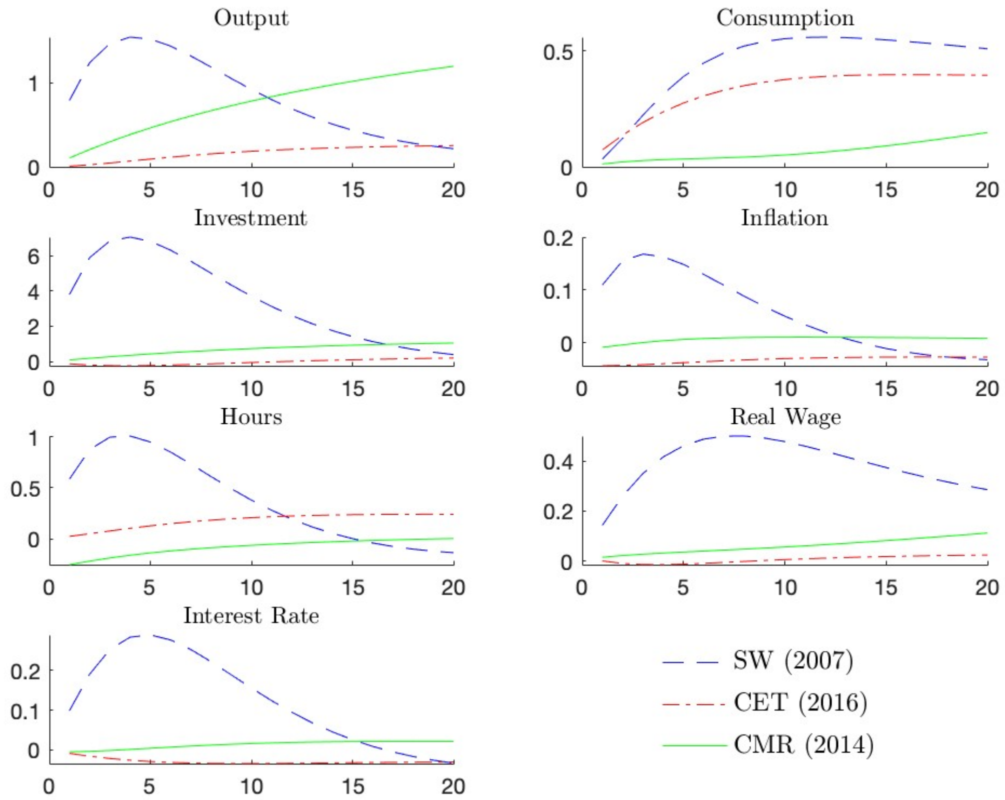

Figure 4. Model Comparison: Investment-specific Technology Shock. Blue, dotted line: (Smets and Wouters, 2007) (SW); Red, dash-dot line: (Christiano et al., 2016) (CET); Green, solid line: (Christiano et al., 2014) (CMR).

pressures. However, both then decline as the effects of the shock diminish and the instrument takes hold, indicating a small and controlled inflationary response.

Moreover, the shock to the investment-specific technology process affects not only the Euler equation for investment but also the equation of motion for capital (Smets and Wouters, 2007). It is influenced, among other things, by the efficiency of investment which is explained by the investment-specific technology shock (Smets and Wouters, 2007). Unsurprisingly, this disturbance accounts for most of the variation in investment, specifically 79 %, as demonstrated in the variance decomposition in Figure 2. In addition, it drives a significant portion of the variance in hours worked and output, the latter particularly in the short run (Smets and Wouters, 2007).

The CET model shows less hump-shaped responses than the SW framework, indicating a more persistent effect of an investment-specific technology shock. The IRFs of the two models CET and CMR are hardly comparable to the SW model, so the responses are shown separately in Figure 5. To observe the trajectories of CET in further detail, see Figure A.5. In the CET model,

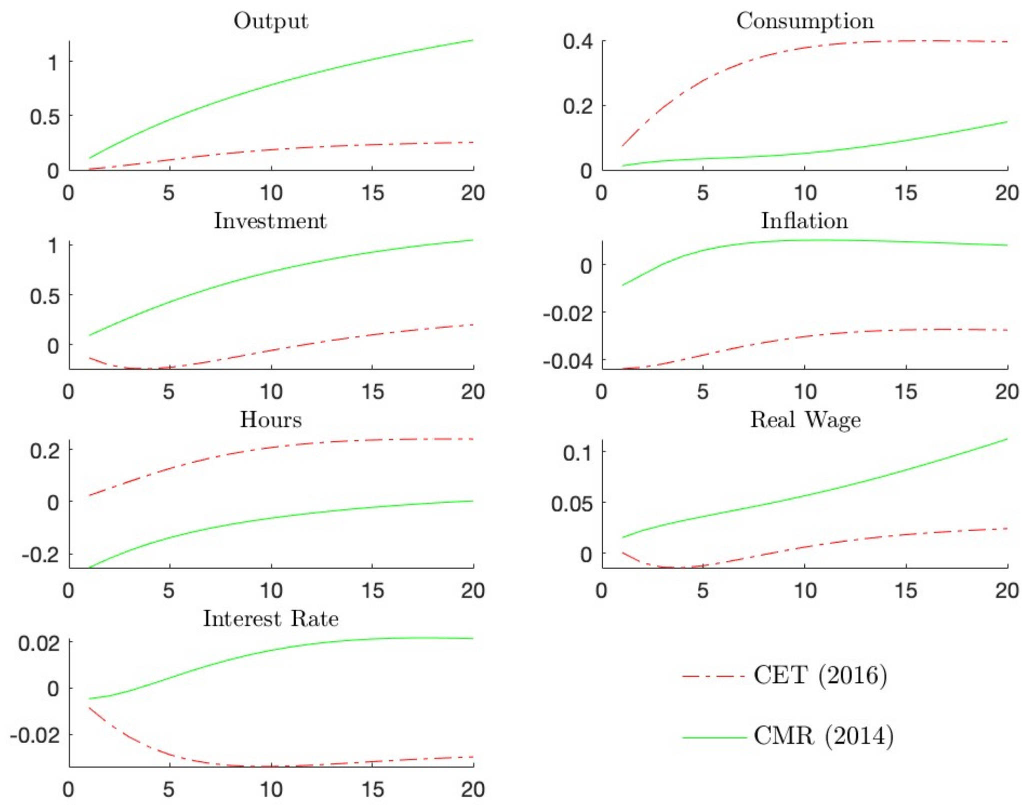

Figure 5. Model Comparison: Investment-specific Technology Shock to CET (2016) and CMR (2014). Red, dash-dot line: (Christiano et al., 2016) (CET); Green, solid line: (Christiano et al., 2014) (CMR).

the response of output is characterised by a steady and continuous rise, indicating a consistently positive impact on the economy, albeit at a modest rate. Consumption shows a more pronounced increase, mirroring the response observed in the SW model. Investment initially experiences a slight drop and a subsequent gradual decrease in the first few periods, possibly due to relatively high investment adjustments costs. However, it eventually begins to rise again at a steady rate, reflecting growing confidence and economic activity. Inflation sees a sharp initial decline, and while it begins to increase shortly after, it remains negative overall, indicating that deflationary pressures persist. The interest rate initially drops and continues to decline further before it gradually increases again. This pattern suggests that the central bank initially lowers interest rates to support the economy but begins to raise them again as inflation gradually increases, aiming to maintain economic stability. Hours worked reflect a modest rise in labour demand, similar to the positive trends in output and consumption. The real wage shows a relatively small reaction due to wage inertia, as with the other two shocks (Christiano et al., 2016). It also follows a similar trajectory as the investment response, with a slight initial decline before rising steadily, which signifies improving labour market conditions. Although not shown in Figure 5, the investment-specific technology shock is the only one which has a long-term effect on the relative price of investment (Christiano et al., 2016). The variance decomposition shows that the contribution of the investment-specific technology shock to the variance of the observed variables is minimal, with at most 10 % explained by this shock, suggesting that other factors, such as monetary policy and neutral technology shocks, play a larger role.

The impulse response functions of the CMR model to an investment-specific shock are presented in Figure 5 and, in more detail, in Figure A.6. The shock has a positive effect on the macroeconomic variables output, consumption, investment and real wages. The responses resemble the trends of the CET framework rather than creating hump-shaped responses as in the SW model. In the CMR model, households adjust their consumption stream gradually at a more modest rate compared the models of SW and CET. As expected from an investment-specific technology shock, investment starts to increase over time, although not as much as in the SW model. Just as for the CET model, inflation initially drops as the shock commences, before starting to increase steadily suggesting that the shock leads to higher demand and economic activity, which the central bank counteracts by gradually raising interest rates to maintain economic stability. The indicators related to labour dynamics such as hours worked initially drop more drastically than the respective response of the CET model. However, this decline is temporary, and hours worked begin to rise, reflecting rising labour demand as the economy expands. Similarly to the SW framework, real wages increase initially and henceforth steadily. According to the variance decomposition depicted in Figure 2 it becomes apparent that the investment-specific technology shock explains 44 %. of the variance in investment, making it the primary driver like in the SW study. The investment-specific and neutral technology shocks each explain around 36 % of the variance in output, together they account for a large part of the variation in output.

4.2 Sensitivity Analysis of IRFs to Parameter Variations

The following part of the study is dedicated to a sensitivity analysis of the real and nominal frictions in the models. For this reason, nominal frictions such as price and wage stickiness as well as real frictions such as investment adjustment costs are analysed in more detail. The impulse response functions are recomputed for the three models, with each parameter being perturbed individually to illustrate how adjustments to parameters affect the dynamics of the model.

4.2.1 Calvo Parameter Price Stickiness

First, the IRFs of the three models are examined with regard to changes in the Calvo (1983) price parameter, denoted as ξ_p. The modes of the posterior distributions are taken as a baseline here, reported in Table 1. Given the strong similarity between the values for CET and CMR, it is reasonable to conclude that only one of the two values is necessary for the purposes of the analysis. In this case, the value of CET, 0.75, is sufficient to account for the stickier price calibration. In Figure 6 the responses of the models to a monetary policy shock are depicted, each one of them observed with a more sticky as well as a more flexible degree of price stickiness. It becomes evident that, if prices are more sticky, so that less firms can adjust their prices optimally, the responses show a more pronounced effect compared to a lower Calvo parameter value. Therefore, with sticky prices, the response is more strongly negatively pronounced for SW and CMR and more positively for the CET model. Throughout the observed variables, the models of SW would respond more intensively to a contractionary monetary policy shock if prices would be more sticky. The CMR model also confirms this observation, although the framework is less distinctive and not particularly sensitive to changes in price stickiness when

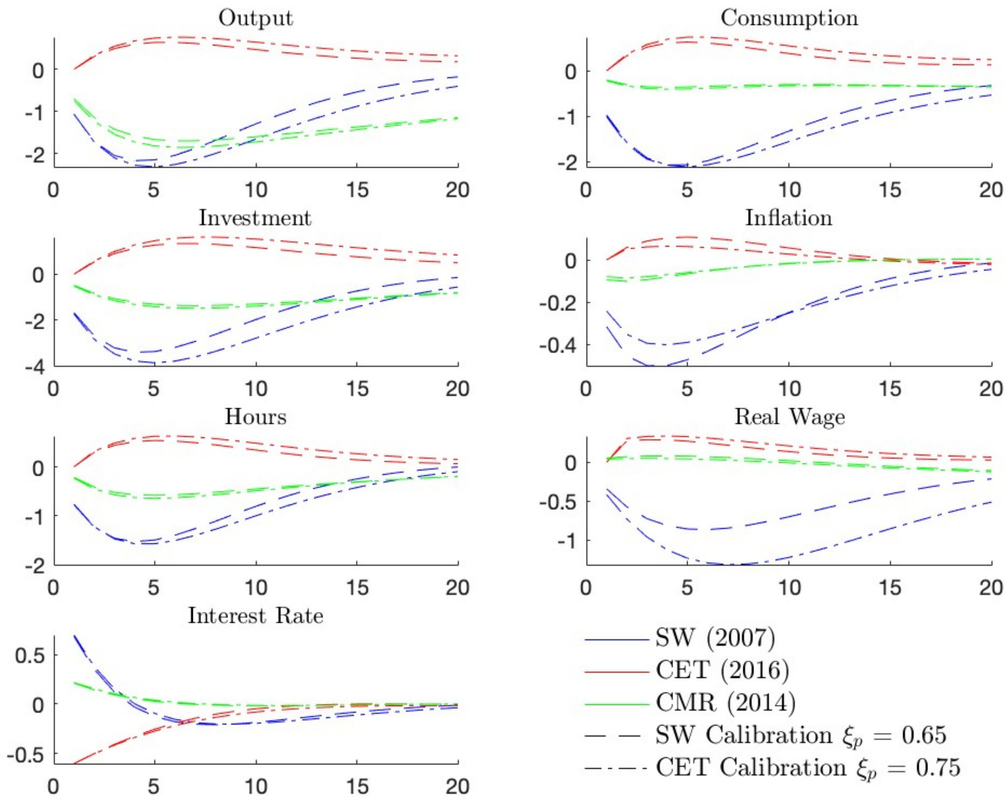

Figure 6. Sensitivity Analysis: Calvo Parameter Price Stickiness. Monetary Policy Shock to SW (2007), CET (2016), CMR (2014). Colors indicating the models: Blue: SW (2007); Red: CET (2016); Green: CMR (2014). Line styles indicating calibration: Dashed line: SW Calibration $\xi_p = 0.65$; Dash-dot line: CET Calibration $\xi_p = 0.75$.

considering a shock to monetary policy. In general, if prices are more sticky, a contractionary monetary policy shock has a stronger negative impact because the economy cannot adjust as quickly to the new conditions, leading to larger declines in economic activity (Henkel, 2020). Moreover, if the model with search and matching frictions CET would have the same price stickiness calibration as the SW model, the IRFs would be more moderate. The SW and CET model show a higher sensitivity regarding perturbations of the Calvo parameter. The sensitivity for SW is especially striking for output, investment and real wages. The CET model shows larger changes in investment and output as well but not as much in real wages because of wage inertia. In addition, Christiano et al. (2016) found that the response to the monetary policy shock is more sensitive to the perturbation than the other two shocks, as evident in Figure A.7 and Figure A.8.

This indicates that the monetary policy impulse response provides the majority of the information about these parameters (Christiano et al., 2016).

In the first few periods the SW model experiences a sharper drop in inflation than it would have with a lower flexibility of prices but is in return able to adjust more quickly to the varying conditions of the economy. The same inflation dynamics apply to the CMR and the CET framework as well although in a more modest way. This highlights the role of price flexibility in mitigating inflationary pressures more quickly, as seen in the CET model (Dedola et al., 2024). Conversely, in the SW and CMR frameworks, price flexibility allows inflation to rise more rapidly, aiding the economy's recovery from a negative inflation rate (Dedola et al., 2024). The real interest rate is less responsive to shocks when prices and wages are sticky compared to a more flexible calibration of prices and wages, confirming Christiano et al. (2010b). In summary, flexible prices allow for quicker adjustments, resulting in a less severe response to the same shock (Dedola et al., 2024; Henkel, 2020).

The same overall results on the macroeconomic indicators can be observed for an investment-specific technology shock as well, see Figure A.8. Model calibrations with higher price stickiness show a more pronounced response when the economy is disturbed by an investment-specific shock to technology. The differences are particularly visible for the SW model but there is almost no sensitivity to changes in the parameter observable for the other two models. In contrast, the impulse response functions to a neutral technology shock exhibit a different pattern to the results observed before, as visible in Figure A.7. In this scenario, the SW model shows more pronounced responses for the flexible price calibration, for the variables output, consumption, investment and real wage. Further, the negative effect on hours worked is not as strong than it would be if prices are slower in adjusting to changes economic conditions. The inflation and interest rate responses display an initially stronger fall but are able to recover more quickly due to prices being more flexible. The same dynamics can be observed for the CET model as well, with a slightly higher response of consumption if prices are more rigid. However, the sensitivity to changes in price stickiness are moderate. Furthermore, the CMR model shows a more positive response for the sticky price calibration. This is in contrast to the responses of the other two frameworks and more in line with the results of the shock to investment-specific technology. These responses can be observed for the variables output, consumption, investment as well as hours worked. In all models, however, a lower degree of price stickiness leads to a larger fall in inflation and interest rates, as prices can adjust more quickly to the cost reductions caused by a neutral technology shock. This effect is significantly more pronounced for the CMR model with flexible prices, leading to less pronounced responses and earlier declines in the key macroeconomic variables.

4.2.2 Calvo Parameter Wage Stickiness

The second nominal friction analysed is the Calvo (1983) wage parameter denoted by ξ_w. This parameter indicates the degree of wage rigidity by specifying how long wages remain unchanged (Romer, 2018). Since in the CET model wages are not conditional on Calvo-style rigidities, but are derived through bargaining between firms and workers (Christiano et al., 2016), they are not subject to this specific analysis. The corresponding posterior mode for the SW model is 0.73, implying that wages adjust on average only once every four periods (Smets and Wouters, 2007). On the other hand, the CMR framework reports a point estimate of 0.81, suggesting that wages change only once every five periods, indicating even greater wage stickiness (Christiano et al., 2014). Figure 7 shows the impulse response functions of the two models with their own Calvo wage parameter calibrations after observing the data, as well as the perturbation results with the value of the respective other model. The sensitivity analysis for the wage stickiness parameter to a contractionary monetary policy shock reveals similar results to those for the price parameter.

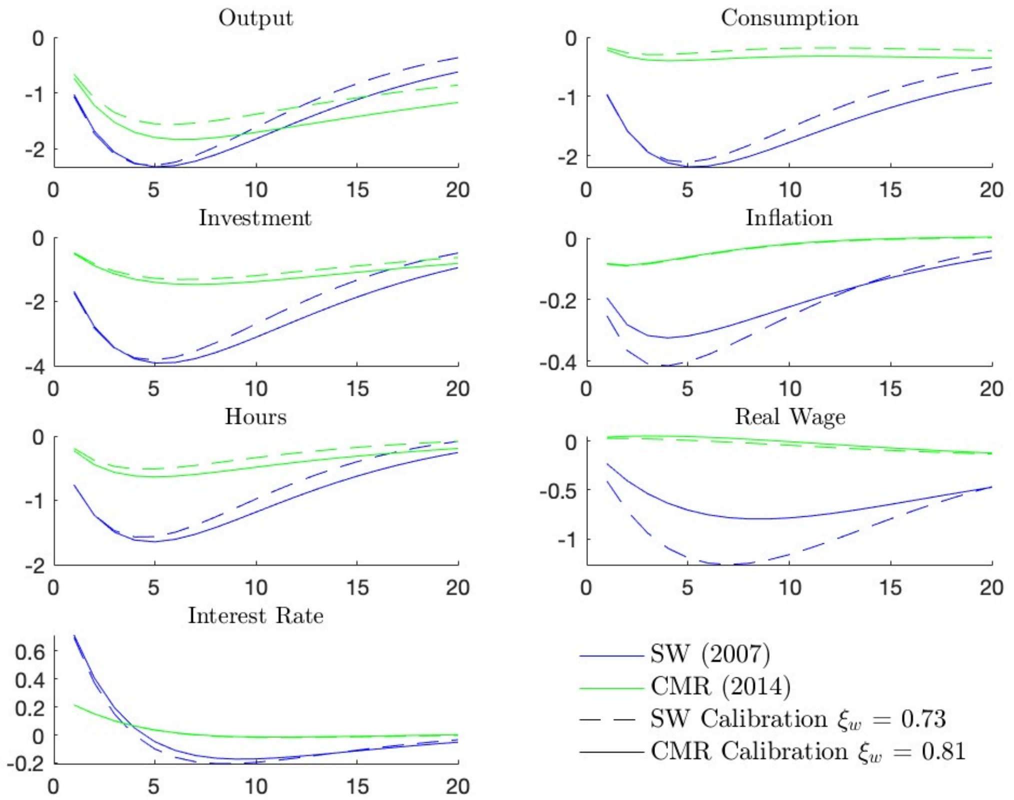

Figure 7. Sensitivity Analysis: Calvo Parameter Wage Stickiness. Monetary Policy Shock to SW (2007), CMR (2014). Colors indicating the models: Blue: SW (2007); Green: CMR (2014). Line styles indicating calibration: Dashed line: SW Calibration $\xi_w = 0.73$; Solid line: CMR Calibration $\xi_w = 0.81$.

In both models, a higher degree of wage stickiness has a more negative effect than if wages were more flexible, for almost every observed indicator. The results suggest that price and wage stickiness have a broadly similar impact on the transmission of a contractionary monetary policy shock, resulting in the same responses on almost all macroeconomic variables.

However, real wages are the exception to these results. The negative impact of a contractionary monetary policy shock on real wages is more pronounced when wages are flexible. In contrast, when wages are sticky, the adjustment process is slower, resulting in a less severe decline in real wages. Although, the sensitivity for the CMR model is notably lower compared to the SW model, the flexible wage calibration exhibits a stronger decline in real wages as well. However, the underlying trend that flexible wages result in a greater drop in real wages is consistent across both models, highlighting the role of wage flexibility in amplifying the response to economic shocks (DeLong and Summers, 1986; Galí and Monacelli, 2016). In both models, varying the stickiness parameter of wages does not change the overall trend in real wage responses. In the CMR response, wages initially rise slightly but then decline. In contrast, in the SW model, real wages decline initially but then recover as the economy adjusts. Although the SW model would approach the CMR model with higher wage stickiness, the dynamics remain different due to the distinct mechanisms and dynamics at play in each framework. In addition, the neutral technology shock, depicted in Figure A.9, reveals that the sticky wage calibration shows slightly stronger responses for the SW model. This dynamic contrasts with the effects of price stickiness on the responses to a neutral technology shock, which affects most economic variables differently, except for real wages, where the responses are consistent across different levels of stickiness. Again, flexible wages lead to a stronger positive response of real wages in particular, mirroring the responses of the sensitivity analysis to price stickiness. The CMR model, on the other hand, exhibits a slightly larger impact when wage stickiness is reduced towards a more flexible rate. In this case, greater wage flexibility would bring the responses from the CMR model closer to the SW model, but would not prevent the observed sharp declines in inflation and hours worked. However, the sensitivity of both models is considerably lower in response to a neutral technology shock. The reaction of the SW model in response to an investment-specific technology shock, see Figure A.10, mirrors its reaction to the perturbation results of the price stickiness parameter. However, the real wage response differs as well. With more flexible wages, the real wage shows a stronger positive reaction. This pattern indicates that while wage stickiness tends to amplify the overall positive effects of the shock on the economy, flexible wages allow real wages to adjust more rapidly and positively to the increase in productivity (Spencer, 1998). The CMR model shows a slightly larger effect when wages are more flexible, similar to its response to a neutral technology shock. However, despite this, the overall sensitivity of the model to the investment-specific technology shock remains low. In summary, the IRFs for both SW and CMR show that wage flexibility primarily affects the labour market rather than broader economic outcomes. The distinct difference in the real wage response when wages are more flexible highlights its importance in shaping how wages adjust to economic shocks, even if other economic variables respond similarly to both price and wage stickiness (Christiano et al., 2005).

4.2.3 Investment Adjustment Cost Parameter

Nominal frictions such as price and wage rigidities are important in capturing the dynamics of the model (Christiano et al., 2005). However, regarding real frictions, investment adjustment costs play an important role as well (Smets and Wouters, 2007) and are therefore examined further in this section. The highest calibration of the investment adjustment cost parameter S'' is that in the CET study, with a posterior mode value of 15.70 (Christiano et al., 2016). This is followed by the value in CMR with a point estimate of 10.78 and finally the lowest calibration is that in the SW model with a value of 5.48 (Christiano et al., 2014; Smets and Wouters, 2007). The impulse response functions of the three models to a neutral technology shock are presented in Figure 8. Each model is shown with its own calibration of investment adjustment costs and with the respective calibrations of the other two models. Since the sensitivity of the CET model is relatively small, Figure A.12 shows its IRFs in more detail. Nevertheless, the responses of all three models to a neutral technology shock show stronger positive effects on output, consumption, investment and real wages when investment adjustment costs are lower. For the indicators of inflation, interest rates and hours worked, where an initial negative effect is observed, the reaction is less pronounced when adjustment costs are lower. Overall, this suggests a faster adjustment to the positive conditions and a faster recovery from the negative effects of a neutral technology shock (Torres, 2020). In the first part of the analysis, it is assumed that the responses of CET and CMR to some macroeconomic variables might be dampened compared to the responses of SW due to greater rigidities, such as higher adjustment costs for investment (Smets and Wouters, 2007). The results, especially the responses of output and investment, show that CET and CMR with a more relaxed calibration of adjustment costs would exhibit an even stronger and, for the CMR model, a more hump-shaped response, approaching the IRFs of SW (Christiano et al., 2005; Groth and Khan, 2010).

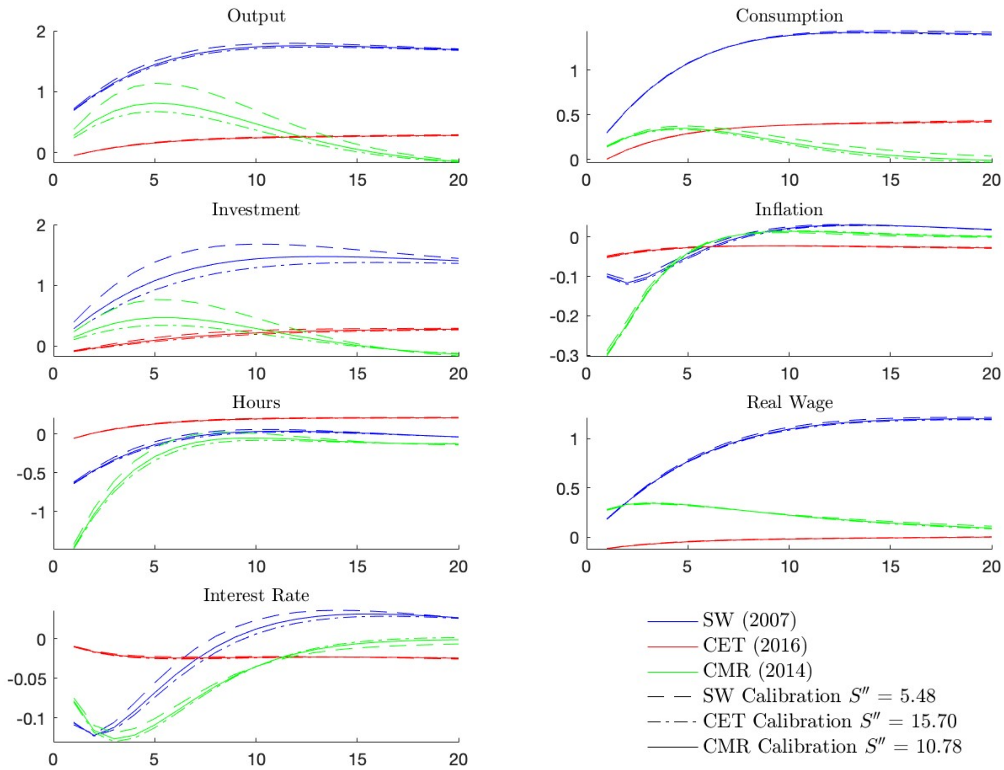

Figure 8. Sensitivity Analysis: Investment Adjustment Cost Parameter. Neutral Technology Shock to SW (2007), CET (2016), CMR (2014). Colors indicating the models: Blue: SW (2007); Red: CET (2016); Green: CMR (2014). Line styles indicating calibration: Dashed line: SW Calibration $S'' = 5.48$; Dash-dot line: CET Calibration $S'' = 15.70$; Solid line: CMR Calibration $S'' = 10.78$.

A notable sensitivity to changes in the investment adjustment cost parameter is also observed in Figure A.11, which shows the IRFs to a monetary policy shock. Similar to the results for the neutral technology shock, in all three models the response is most pronounced when investment adjustment costs are lowest. As demonstrated in Christiano et al. (2005), the presence of investment adjustment costs leads to hump-shaped responses of key indicators such as output, investment and consumption. Conversely, when the CET calibration for adjustment costs is implemented, the responses are more muted, reflecting the higher costs of adjusting to economic changes (Justiniano et al., 2010). Furthermore, as investment adjustment costs in the SW model rise to the level of CMR-like costs, the model approaches the CMR response, particularly when investment and hours worked are examined. This illustrates the similar dynamics of the two models, with the striking differences being in the degree of rigidities (Christiano et al., 2005). Finally, the results of investment adjustment cost perturbations to an investment-specific technology shock are examined, as displayed in Figure 9. As in the broader analysis, this shock shows a

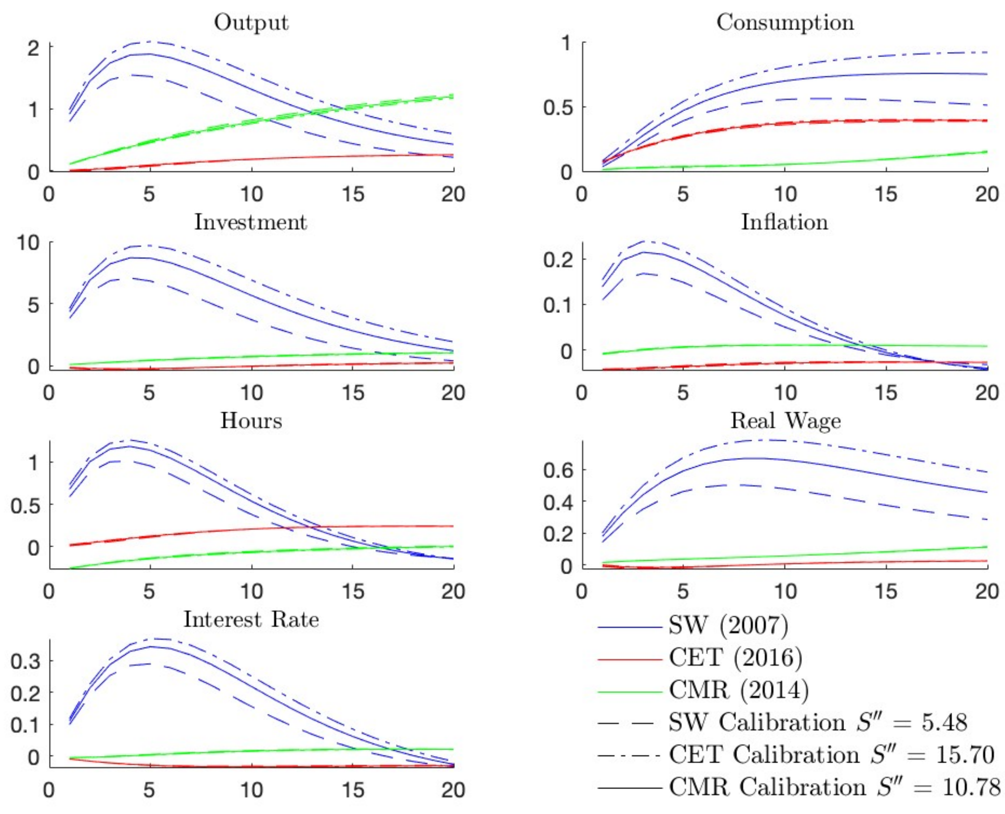

Figure 9. Sensitivity Analysis: Investment Adjustment Cost Parameter. Investment-specific Technology Shock to SW (2007), CET (2016), CMR (2014). Colors indicating the models: Blue: SW (2007); Red: CET (2016); Green: CMR (2014). Line styles indicating calibration: Dashed line: SW Calibration S'' = 5.48; Dash-dot line: CET Calibration S'' = 15.70; Solid line: CMR Calibration S'' = 10.78.

strong reaction of the SW model but an undersized response and less sensitivity of the other two models. Therefore, in order to investigate the dynamics of CET and CMR and compare them with the SW model, Figure 10 presents the responses of the two models in more detail. The IRFs

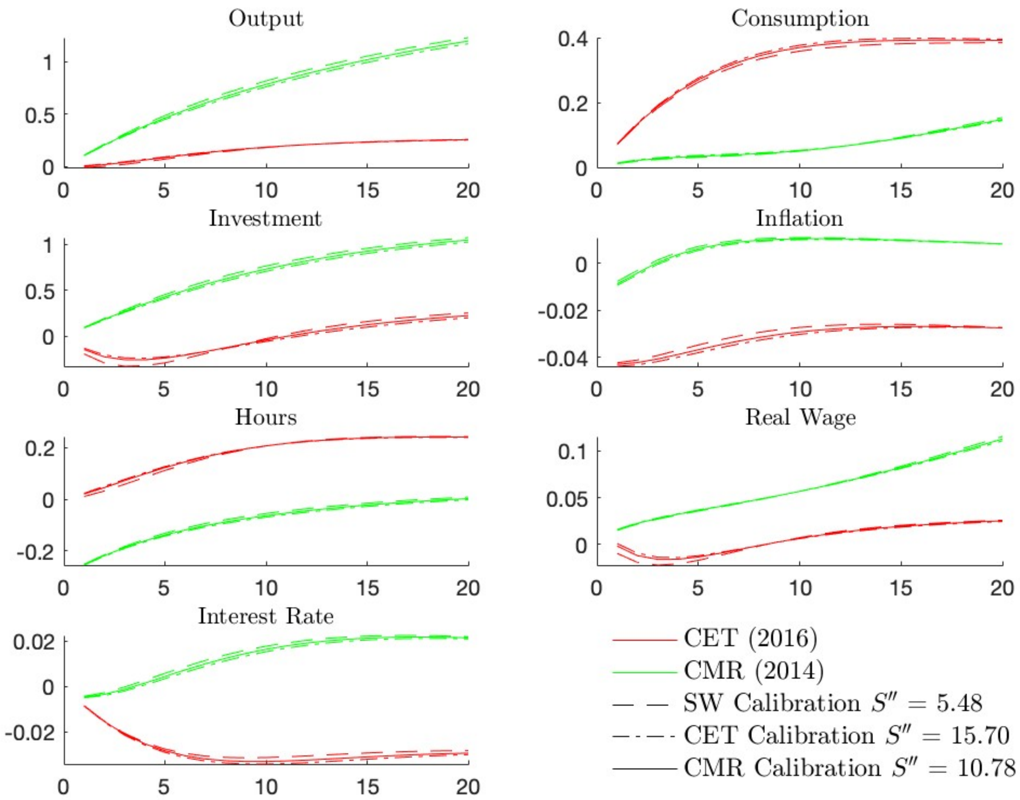

Figure 10. Sensitivity Analysis: Investment Adjustment Cost Parameter. Investment-specific Technology Shock to CET (2016) and CMR (2014). Colors indicating the models: Red: CET (2016); Green: CMR (2014). Line styles indicating calibration: Dashed line: SW Calibration $S'' = 5.48$; Dash-dot line: CET Calibration $S'' = 15.70$; Solid line: CMR Calibration $S'' = 10.78$.

of the SW model show more pronounced responses when higher investment adjustment costs are implemented, such as the calibrations of CET or CMR. This is in contrast to the results for the neutral technology shock, where lower adjustment costs show more pronounced responses. Conversely, with lower investment adjustment costs the peak of the macroeconomic variables is reached earlier. Different patterns emerge for the CET and CMR models. The CMR model shows slightly more positive responses when adjustment costs are lower for output, consumption, investment, real wages and the interest rate. In addition, the negative effects on the inflation rate and the number of hours worked are not as pronounced as they would be with higher investment adjustment costs. Furthermore, the CET model shows similar trends to SW only in terms of consumption. The other responses, such as output and hours worked, tend to be more muted initially or, as in the case of investment and real wages, to show a more pronounced fall for a calibration with lower adjustment costs. However, all are followed relatively quickly by a recovery, demonstrating the dynamic effects of lower costs. Comparing the models, the CMR model with lower adjustment costs shows more pronounced IRFs and generally approaches the responses of the SW model with its original calibration, particularly when focusing on the output response. Furthermore, the CET model shows a significant initial drop in investment, a pattern not observed in the SW and CMR models. If the adjustment costs of CET were lower, the initial drop would be even more pronounced, although the recovery would be faster than in the original calibration. Since this reaction cannot be replicated with the other two models, even with much higher investment adjustment costs, this parameter alone cannot explain investment dynamics in the CET framework.

5 Discussion

The following section combines the results of the impulse response function and sensitivity analyses with the findings from the literature review. The focus is on how the various frictions and underlying dynamics affect the responses to the different shocks employed and to variations in key parameters. Furthermore, by comparing the strengths and weaknesses of each model, the mechanisms at play and their implications for understanding macroeconomic dynamics are assessed. Finally, the limitations of the analysis and the associated models are discussed and suggestions for further research are made.

To understand the different behaviours of each model, it is crucial to examine the underlying mechanisms that drive their responses to several economic shocks. First, the Smets and Wouters (2007) model stands out as a robust baseline in the analysis. It captures the broad fluctuations of an economy by including both nominal and real frictions, such as price and wage stickiness, partial indexation, investment adjustment costs, habit formation, capital utilisation and fixed costs of production. (Smets and Wouters, 2007). In addition, the SW model features a Kimball (1995) aggregator which allows for a time-varying elasticity of substitution that depends on the relative price of the good (Harding et al., 2022; Smets and Wouters, 2007). This results in a more realistic representation of consumer demand due to reduced sensitivity to price changes when consumption levels are already high (Lisack et al., 2022). This feature also contributes to a more nuanced understanding of how quickly prices and wages adjust to the respective mark-up. In particular, the speed of adjustment is determined by the degree of stickiness, the curvature of the Kimball aggregator, partial indexation and the share of fixed costs in production (Smets and Wouters, 2007). Further, investment adjustment costs are modelled as an elasticity of the cost of changes in investment, which is useful for capturing the hump-shaped responses of investment to different shocks (Christiano et al., 2005). This gradual adjustment can be observed in the analysis when looking at the IRFs to a monetary policy or investment-specific shock.

Second, the Christiano et al. (2016) model addresses some of the limitations of traditional DSGE models by introducing labour market frictions through a search and matching framework. Furthermore, it provides a more nuanced view of wage setting by allowing wages to be determined through an alternating offer bargaining process, rather than being constrained by Calvo-style rigidities as in SW and CMR (Christiano et al., 2016, 2014; Smets and Wouters, 2007). Along with this assumption also goes the feature that wages are inertial, leading to a more gradual adjustment of wages (Christiano et al., 2016). Moreover, this wage inertia has important implications for how the model responds to shocks, particularly in terms of inflation dynamics (Christiano et al., 2005). The AOB model provides a more robust analysis of labour market variables and addresses policy issues beyond the scope of the NK Calvo sticky wage models, as the statistical fit of these models is overly dependent on the indexation assumption, which lacks strong empirical support (Card, 1986; Christiano et al., 2016; Smets and Wouters, 2007).

Third, the Christiano et al. (2014) model introduces financial imperfections into an otherwise standard NK framework. These take the form of a financial accelerator mechanism, as developed by Bernanke, Gertler and Gilchrist (1999), which introduces an additional financial premium for external financing due to asymmetric information (Gelain et al., 2010). In the model, entrepreneurs borrow from financial intermediaries to finance purchases of capital supplied by households (Foroni et al., 2022). In addition, the demand for capital goods depends on the financial position of entrepreneurs, as the premium covers the cost of possible default (Christiano et al., 2014; Gelain et al., 2010). Moreover, similar to SW, the model features the same set of nominal and real frictions, including price and wage stickiness, partial indexation, habit formation and investment adjustment costs (Christiano et al., 2014; Smets and Wouters, 2007).

The differing responses to a monetary policy shock demonstrate the different mechanisms at play in the three models. The SW and the CMR model implement a contractionary monetary policy shock whereas the CET model implements an expansionary one. As shown in Figure 1, the responses to a contractionary shock are larger than those to the expansionary disturbance, especially for the SW model, confirming Cover (1992); Kim and Ruge-Murcia (2011). Moreover, the CMR model exhibits a smaller response due to the assumptions of Bernanke et al. (1999) on external funding (Christiano et al., 2014; Henkel, 2020). Further, the work of Christiano et al. (2016) highlights that the response to a monetary policy shock is more sensitive to parameter perturbations than to the other two shocks, indicating that the monetary policy impulse response is crucial for understanding these parameters. This leads to discussing the role of nominal rigidities, in particular price and wage stickiness and their impact of monetary policy shocks. Christiano et al. (2005) state that, if wage stickiness is given as a nominal friction, it is not necessary to include price stickiness in order to effectively capture the responses to a monetary policy shock. On the one hand, the sensitivity analysis confirms that price and wage stickiness have broadly similar effects on the transmission of a contractionary monetary policy shock. One the other hand, the picture changes when examining the results of perturbations to the wage stickiness parameter. Here, the response of the real wage is different, with the flexible wage calibration showing a stronger decline (Galí and Monacelli, 2016). This has several implications. First, both price and wage stickiness are important to illustrate the differential impact of a monetary policy shock on real wages. This relevancy of price and wage rigidities is also confirmed by Christiano et al. (2014), who argue that these nominal frictions highlight the importance of their risk shock. Second, it shows how wage flexibility can amplify the impact of economic shocks on the labour market (Galí and Monacelli, 2016), as observable in Figure 7. In summary, greater price and wage stickiness amplifies the negative effects of the contractionary monetary policy shock, as delayed adjustments lead to deeper declines in output, consumption and investment

(Henkel, 2020). In contrast, if prices and wages are more flexible, adjustment happens more quickly, leading to a less severe downturn (Henkel, 2020), except for the response of the real wage (Galí and Monacelli, 2016).

Further, Christiano et al. (2005) state that real wages play a huge part in the challenge of accurately reflecting the observed behavior of inflation in response to an expansionary monetary policy shock. This is due to wage inertia creating only a small wage response to the shock, thus preventing an excessive increase in marginal costs and in the inflation rate (Christiano et al., 2021). This inertia also makes real wages less responsive to such shocks than hours worked (Christiano et al., 2016). Another key variable affected by monetary policy shocks is the response of the interest rate, which is less sensitive to shocks when prices and wages are sticky, as noted by Christiano et al. (2010b). This is confirmed by comparing the IRFs in Figure 1, which show that the response is less pronounced in the CMR model than in the SW model, where wages and prices are more flexible. Moreover, the sensitivity analysis suggests that the response in the SW model would also be smaller if prices or wages were more sticky. In addition, the results confirm that the interest rate is the only variable of CET that is immediately affected by a monetary policy shock, while the other variables react in a more gradual way (Christiano et al., 2016). Finally, all models show hump-shaped responses to the monetary policy shock due to a reasonable value of habit formation, which helps to explain the responses of other key variables, suggesting a deeper investigation of this real friction (Christiano et al., 2005).

Next, the responses to a neutral technology or total factor productivity shock also show the differences between the models. For instance, differences in the responses of hours worked and real wages lead to distinct responses in the inflation rate. Regarding this, the SW model shows a modest initial fall, which can be attributed to the small slope of the New Keynesian Phillips curve and the proactive monetary policy response, which stabilises inflation despite the presence of these shocks (Smets and Wouters, 2007). A striking difference is seen in the CMR model, which shows a large drop in inflation after the shock starts. In the CET model, on the one hand, a neutral technology shock has a larger impact on the inflation response than a monetary policy shock (Paciello, 2011). On the other hand, a neutral shock to technology leads to an increase in productivity, which reduces the marginal cost of production for firms and thus leads to a relatively large reduction in inflation (Christiano et al., 2016).

Similar to the responses to monetary policy shocks, wage inertia plays a key role as it maintains this downward pressure on inflation, as wages adjust slowly, the reduction in marginal costs is sustained and inflation continues to fall (Christiano et al., 2016). Although the fall in the inflation responses of SW and CMR is initially stronger, the exogenously sticky wage assumption leads to a relatively quick recovery in inflation and marginal costs as wages and prices rise more rapidly (Christiano et al., 2014; Smets and Wouters, 2007). Confirming this, Figure A.9 indicates that if wages were more sticky in the SW model, they would follow a similar pattern to the CET model, inhibiting wage increases and thus maintaining lower inflation rates for longer. Overall this highlights how other models may underestimate inflation responses to such shocks and reveals distinct dynamics due to omitted frictions (Christiano et al., 2016).

As noted above, in the CET model, hours worked fall less dramatically in response to neutral technology shocks than in the other models. In the SW and CMR models, a supply-side shock leads to a larger reduction in hours worked due to various rigidities such as price stickiness and investment adjustment costs (Francis and Ramey, 2005; Gali, 1999; Galí and Rabanal, 2004). However, there is a lot of disagreement as alternative views argue that the effect of productivity shocks on labour can also be positive (Christiano et al., 2003; Dedola and Neri, 2007; Peersman and Straub, 2009). Furthermore, there are notable differences in the magnitude and persistence of these effects, with the SW model showing the highest persistence and the CMR model showing

a more transitory nature. This may be due to the relatively high adjustment costs of investment, as responses would be more pronounced at lower costs, but also to the financial accelerator mechanism (Foroni et al., 2022). In general, the CMR model shows a greater sensitivity of output and investment to changes in investment adjustment costs, which is a crucial parameter in a framework with financial frictions (Foroni et al., 2022).
Therefore, if these costs in the SW model were to increase to a level similar to that in the CMR model, the behaviour of the SW model begins to converge to that of the CMR model, particularly in terms of investment and hours worked. This convergence highlights the similar dynamics between the two models, with the main differences being differences in the degree of economic rigidities (Foroni et al., 2022; Groth and Khan, 2010).

Finally, the responses to an investment-specific technology shock provide additional insights into the different underlying dynamics of the models. The SW model displays more pronounced responses to investment-specific technology shocks when higher investment adjustment costs are implemented (Figure 9), compared to the opposite scenario of the results for the neutral technology shock, where lower adjustment costs show more enhanced responses (Figure 8). This is also in contrast to the responses of CET which generally show less pronounced and less sensitive results to this type of disturbance. Similarly, the IRFs of CMR have a much lower sensitivity to changes in investment-adjustment costs due to the presence of the financial accelerator (Christensen and Dib, 2008). A slightly larger sensitivity can be found in the perturbation results to the price stickiness parameter, following Justiniano et al. (2010) with the fact that the transmission of investment-specific technology shocks relies on monopolistic competition including sticky prices and wages.

The following part aims to highlight the limitations of the DSGE models and their analysis by addressing key weaknesses and suggesting directions for further research. Traditional DSGE models are often criticised for relying on a large number of unlikely assumptions that exist primarily to fit historical data, rather than having stable economic parameters (Lucas Jr, 1976). In addition, standard DSGE frameworks simplify labour market dynamics and have a minimal focus on the financial sector (Christiano et al., 2021; Gelain et al., 2010). For instance, the SW model simplifies wage dynamics by assuming exogenously sticky wages and ignores financial frictions in the form of agency problems that exist in real economies (Smets and Wouters, 2007). The CET model introduces labour market frictions through a search and matching framework, but it also has its limitations (Christiano et al., 2016). For example, the model adopts the assumption of Hall and Milgrom (2008) that the costs associated with wage bargaining disagreements show minimal sensitivity to business cycle fluctuations, although the empirical support for this assumption is weak. Furthermore, the importance of wage inertia in labour market dynamics is debated in the literature, with studies such as Christiano et al. (2021), Shimer (2005) and Hall and Milgrom (2008) supporting its importance, while others such as Hagedorn and Manovskii (2008) and Ljungqvist and Sargent (2017) question this perspective. Moreover, the model's treatment of heterogeneous agents and localised labour markets remains underdeveloped (Christiano et al., 2016). Future research could benefit from exploring how wages respond to group-level shocks, such as those related to skills, education or location, which are not adequately addressed in the current framework (Christiano et al., 2016).

Clearly, financial frictions are a critical component of macroeconomic dynamics, which are partly captured by CMR. While this framework incorporates a financial accelerator mechanism, it assumes that risk fluctuations are exogenous, a premise that may not hold in reality (Christiano et al., 2014). The model also assumes that the transfer of funds between households and entrepreneurs is exogenous and independent of changes in the economy, an assumption that needs further investigation as well (Christiano et al., 2014). As a result, the model's ability to forecast financial crises or low-probability, highly non-linear shocks might be limited.

In order to refine this analysis, other structural parameters would have to be examined. For example, although habit formation in consumption is not essential in accounting for inflation or output responses, it plays a central role in shaping the dynamics of other macroeconomic variables (Christiano et al., 2005; Sommer, 2007). Further, Smets and Wouters (2007) explores that a reduction in the level of habit formation leads to reduced responses that are compensated by more persistent exogenous shocks and increased nominal rigidities, demonstrating its shaping effects on the economy. Moreover, variable capital utilisation is essential in capturing inflation inertia and output persistence (Christiano et al., 2005). Further, capital utilisation costs can influence the efficiency of production by optimising the use of factor inputs, the allocation of resources and influence the financial returns for entrepreneurs (Christiano et al., 2014). These findings underscore the importance of including a broader set of parameters in the analysis to better capture real economic fluctuations and the different responses of the models.

To further improve the analysis, it would be beneficial to include a broader set of variables, in particular those related to financial and labour market dynamics. An important additional measure could be the relative price of investment goods (Christiano et al., 2016, 2014). In the labour market, variables such as the unemployment rate, the job finding rate and vacancies would provide a more comprehensive understanding (Christiano et al., 2016). From a financial perspective, examining the net worth of entrepreneurs via the stock market value, credit to non-financial firms, the interest rate spread and the slope of the term structure could provide deeper insights into the interaction between financial conditions and macroeconomic dynamics (Christiano et al., 2014).

One of the main challenges in comparing DSGE models depends on the type of monetary policy shock they implement. For example, while the SW and CMR models both implement contractionary monetary policy shocks, the CET model implements an expansionary shock. This makes it difficult to directly compare the responses of the models.

As investment adjustment costs play a crucial role in determining how quickly firms adjust to changes, the IRFs of SW show a contra-intuitive reaction to an investment-specific technology shock. In this case, higher investment adjustment costs exhibit a stronger response to the shock, suggesting the need for further investigation.

The analysis compares three models based on different assumptions and implications, such as search and matching frictions or financial accelerators. This requires careful interpretation of the results, as generalisability may be limited and structural differences between the models may be overlooked. Despite these limitations, the methodology attempts to address them by taking steps to mitigate the drawbacks such as normalising shock sizes, carefully recalibrating IRFs and consistently applying necessary transformations. In summary, the analysis provides robust insights into model dynamics but should be interpreted with caution due to inherent limitations in model assumptions and sensitivity analysis, highlighting the need for further research on a broader set of parameters.

6 Conclusion

In conclusion, DSGE models are the most popular tool in macroeconomic analysis as they incorporate various frictions, enabling the simulation of dynamic responses to exogenous shocks. However, many standard models fail to capture the complexities associated with labour and financial frictions. This study has explored three prominent DSGE models: The Smets and Wouters (2007) model, the Christiano et al. (2016) model, and the Christiano et al. (2014) model. Each framework incorporates different frictions, providing insights into the responses of key indicators of the economy to the same structural shocks. The shocks analysed include monetary policy, neutral technology, and investment-specific technology, with nominal and real rigidities such as price and wage stickiness, and investment adjustment costs playing critical roles.

The findings of the impulse response function analysis highlight that incorporating labour and financial frictions, in form of modeling wages as an equilibrium outcome and introducing a financial accelerator mechanism, substantially affects inflation and investment responses. In particular, the sluggish adjustment of wages in the Christiano et al. (2016) model is pivotal for understanding the transmission of monetary policy and its effects on inflation. The financial accelerator mechanism showcased in the Christiano et al. (2014) model illustrates how small changes in financial conditions, as for example in investment adjustment costs, can cause significant fluctuations in investment and output, especially in response to neutral technology shocks. The sensitivity analysis further demonstrates that the Smets and Wouters (2007) model exhibits the most pronounced responses and highest sensitivity to parameter perturbations due to its fewer restrictions in the labour markets and the financial sector.

Underestimating the impact of these frictions can lead to incomplete models that fail to capture the complexity of the real economy. A more comprehensive framework that accurately reflects real-world dynamics is needed to improve forecasting performance. Future research should address the deeper integration of these frictions, examine their interactions and evaluate the models against a wider range of economic scenarios, including the assessment of additional shocks and parameters. Such extensions could substantially deepen the understanding of macroeconomic fluctuations and support potential policy interventions to deal with various economic challenges.

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Appendix

Impulse Response Function Analysis of the Models

Monetary Policy Shock

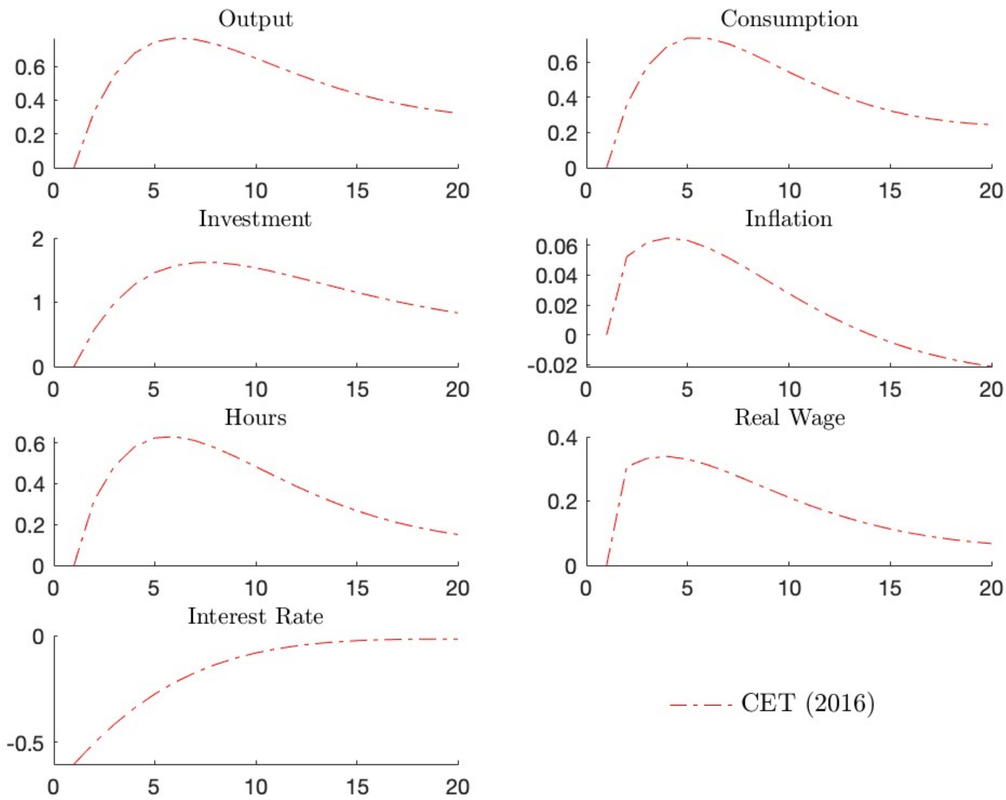

Figure A.1. Monetary Policy Shock to CET (2016).

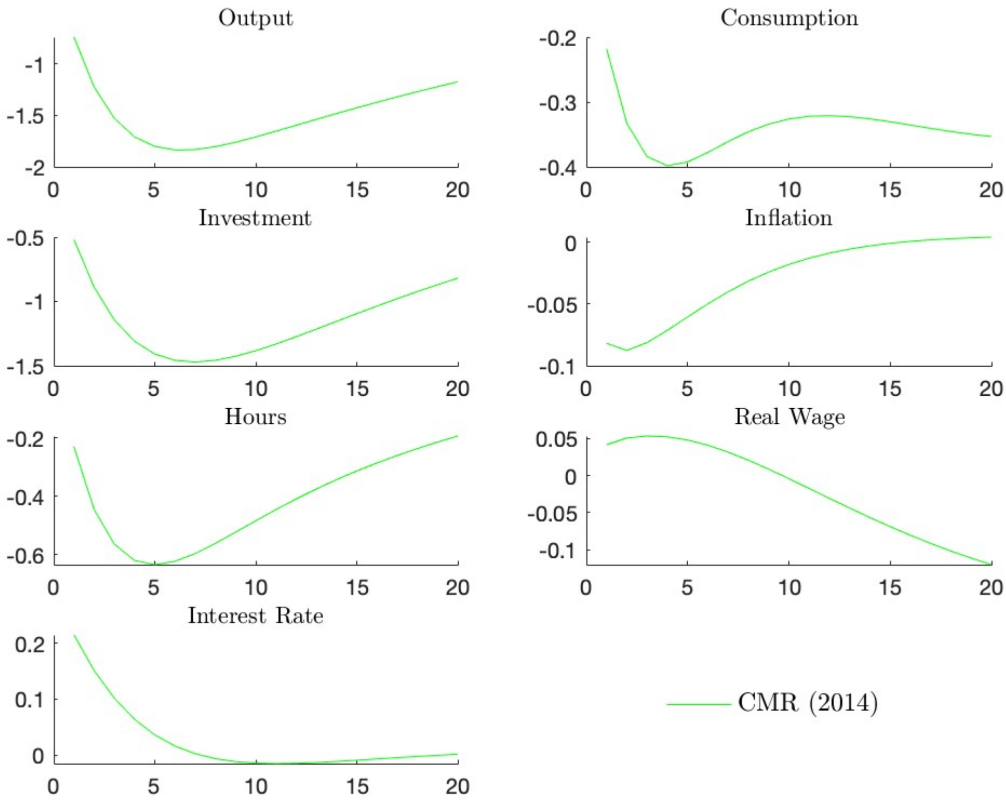

Figure A.2. Monetary Policy Shock to CMR (2014).

Neutral Technology Shock

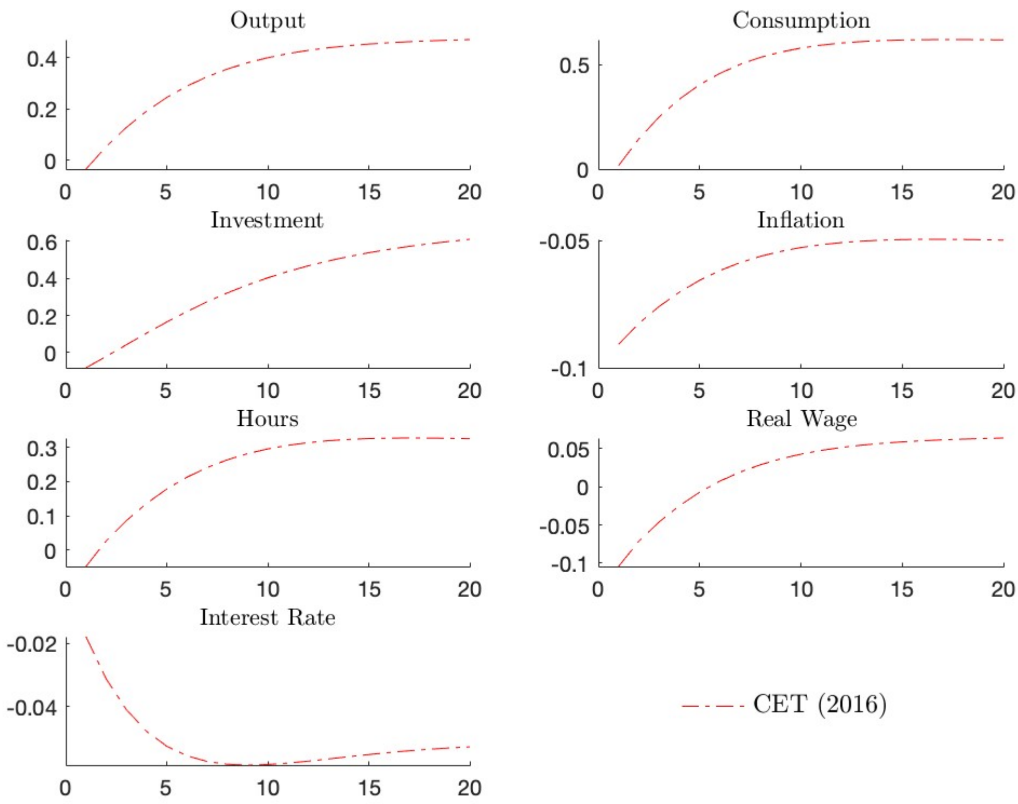

Figure A.3. Neutral Technology Shock to CET (2016).

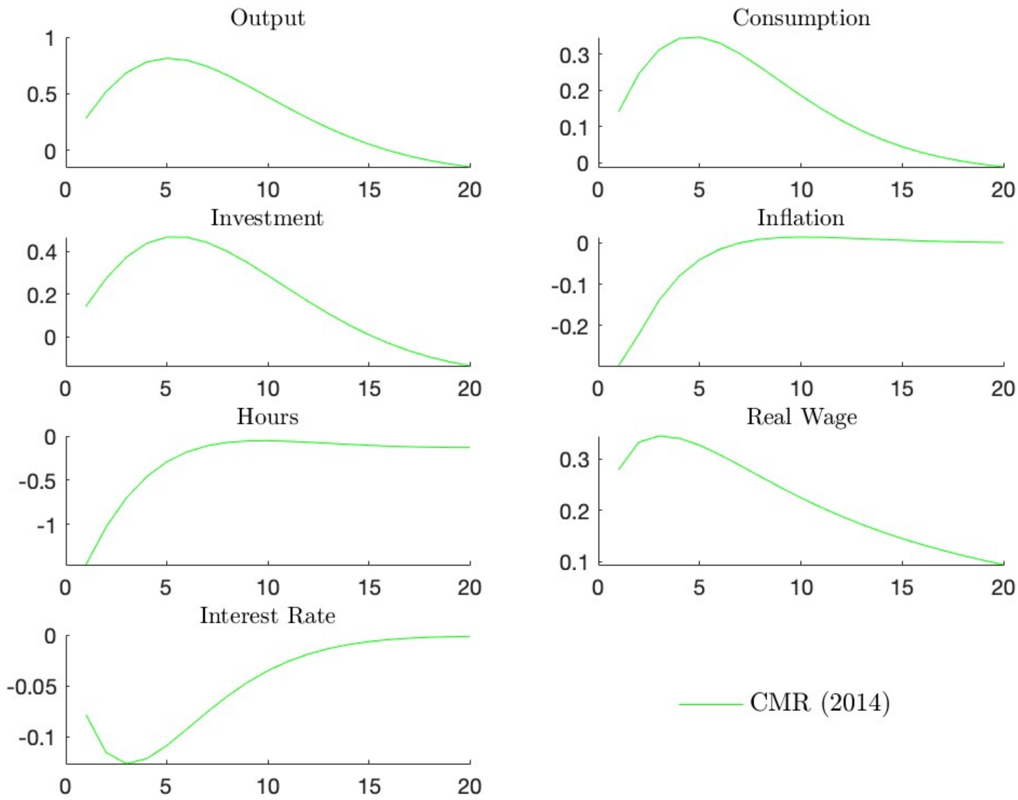

Figure A.4. Neutral Technology Shock to CMR (2014).

Investment-specific Technology Shock

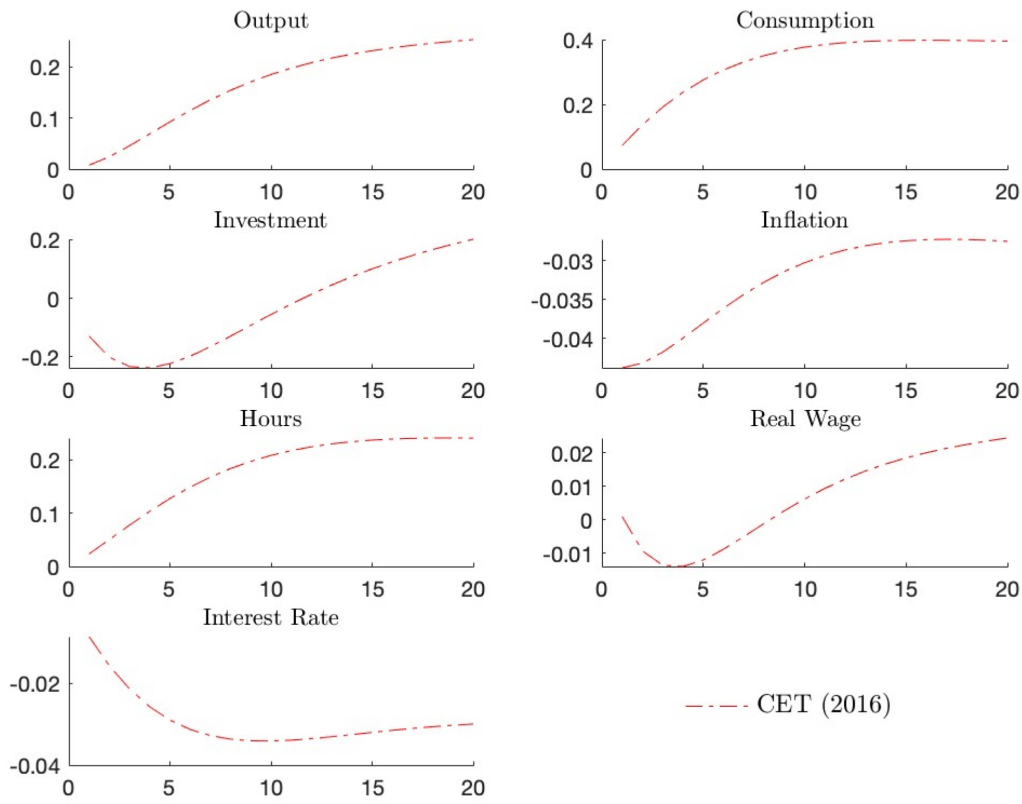

Figure A.5. Investment-specific Technology Shock to CET (2016).

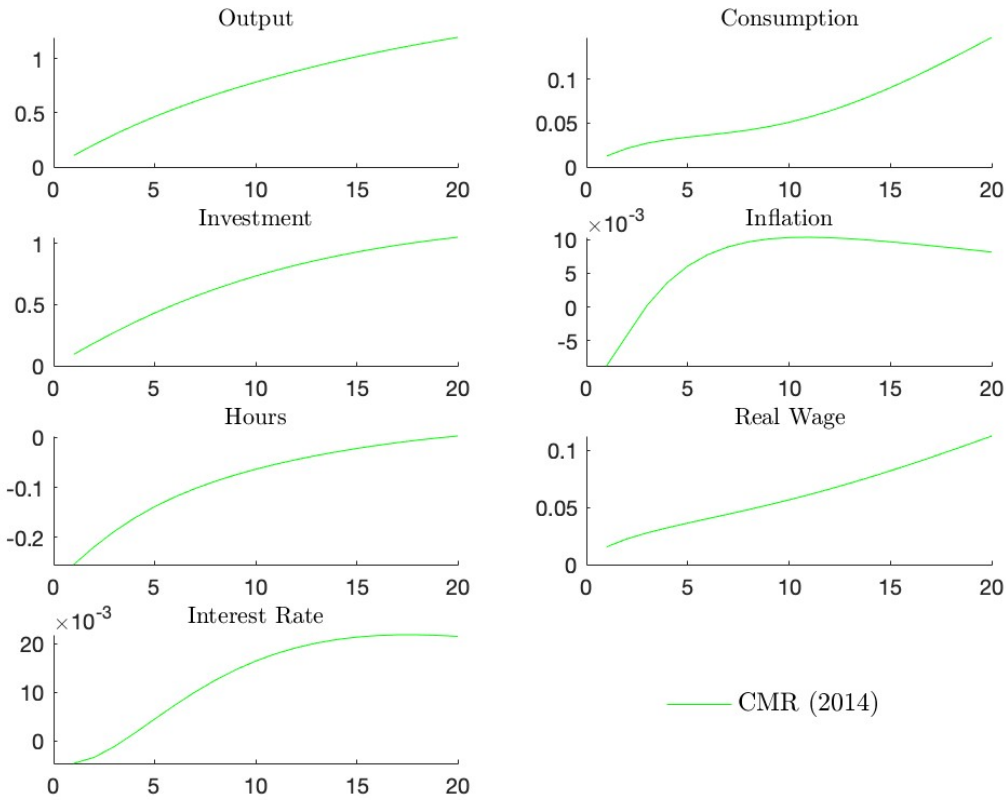

Figure A.6. Investment-specific Technology Shock to CMR (2014).

Sensitivity Analysis of IRFs to Parameter Variations

Calvo Parameter Price Stickiness

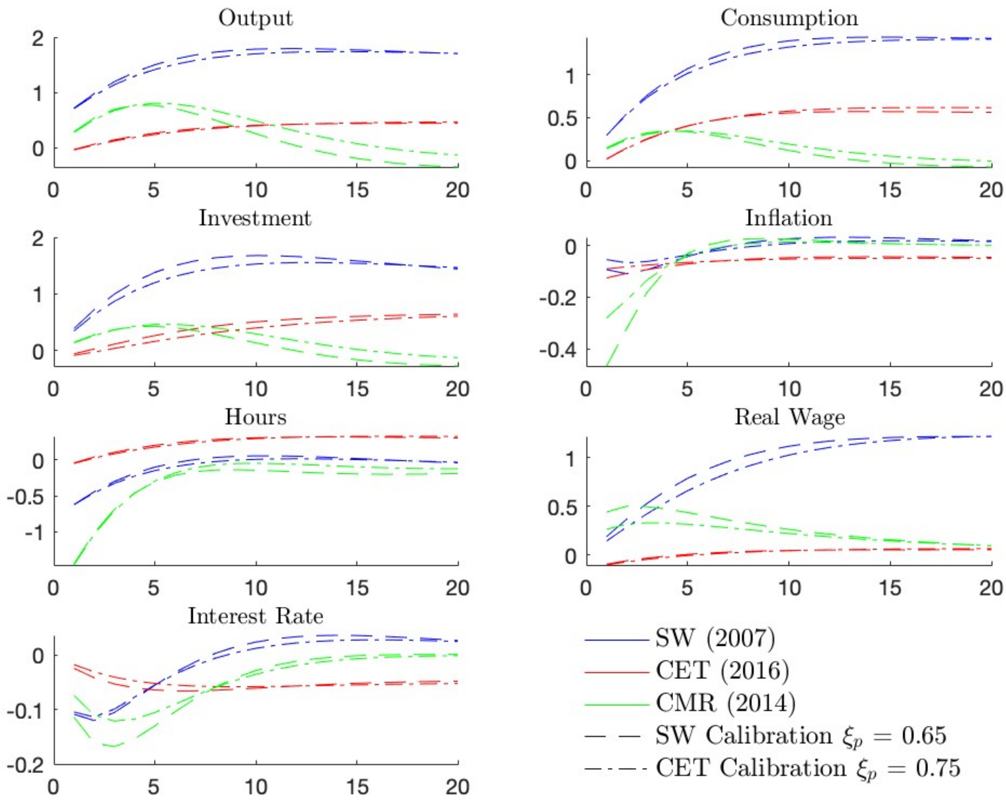

Figure A.7. Sensitivity Analysis: Calvo Parameter Price Stickiness. Neutral Technology Shock to SW (2007), CET (2016), CMR (2014). Colors indicating the models: Blue: SW (2007); Red: CET (2016); Green: CMR (2014). Line styles indicating calibration: Dashed line: SW Calibration $\xi_p = 0.65$; Dash-dot line: CET Calibration $\xi_p = 0.75$.

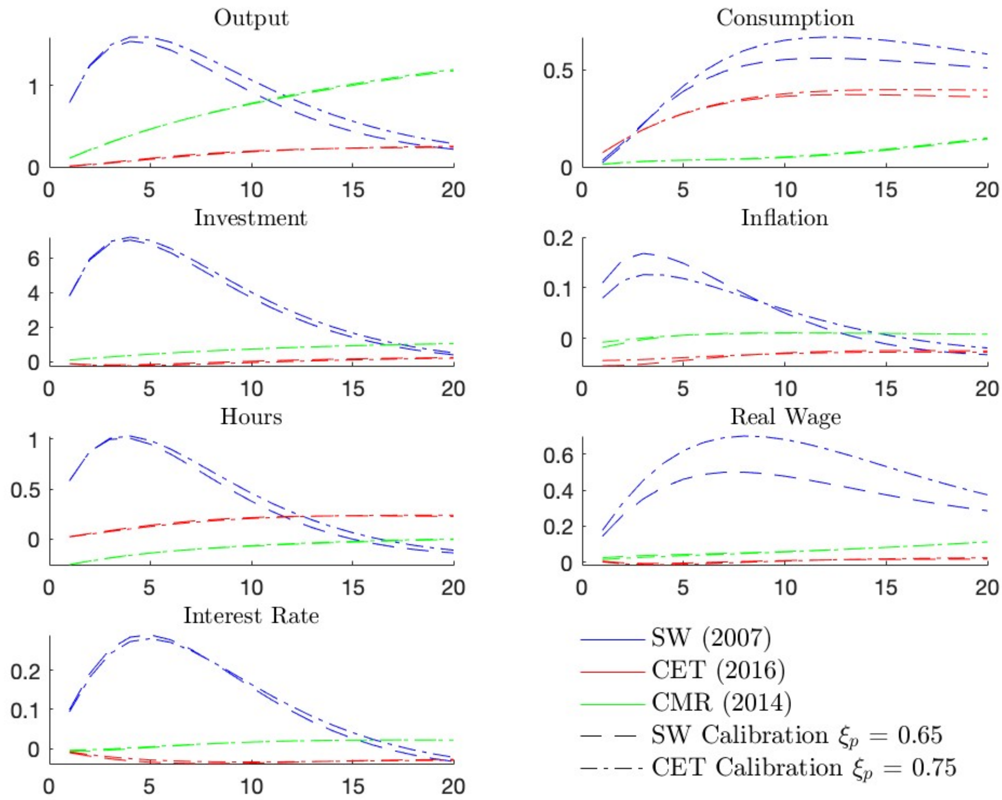

Figure A.8. Sensitivity Analysis: Calvo Parameter Price Stickiness. Investment-specific Technology Shock to SW (2007), CET (2016), CMR (2014). Colors indicating the models: Blue: SW (2007); Red: CET (2016); Green: CMR (2014). Line styles indicating calibration: Dashed line: SW Calibration ξ_p = 0.65; Dash-dot line: CET Calibration ξ_p = 0.75.

Calvo Parameter Wage Stickiness

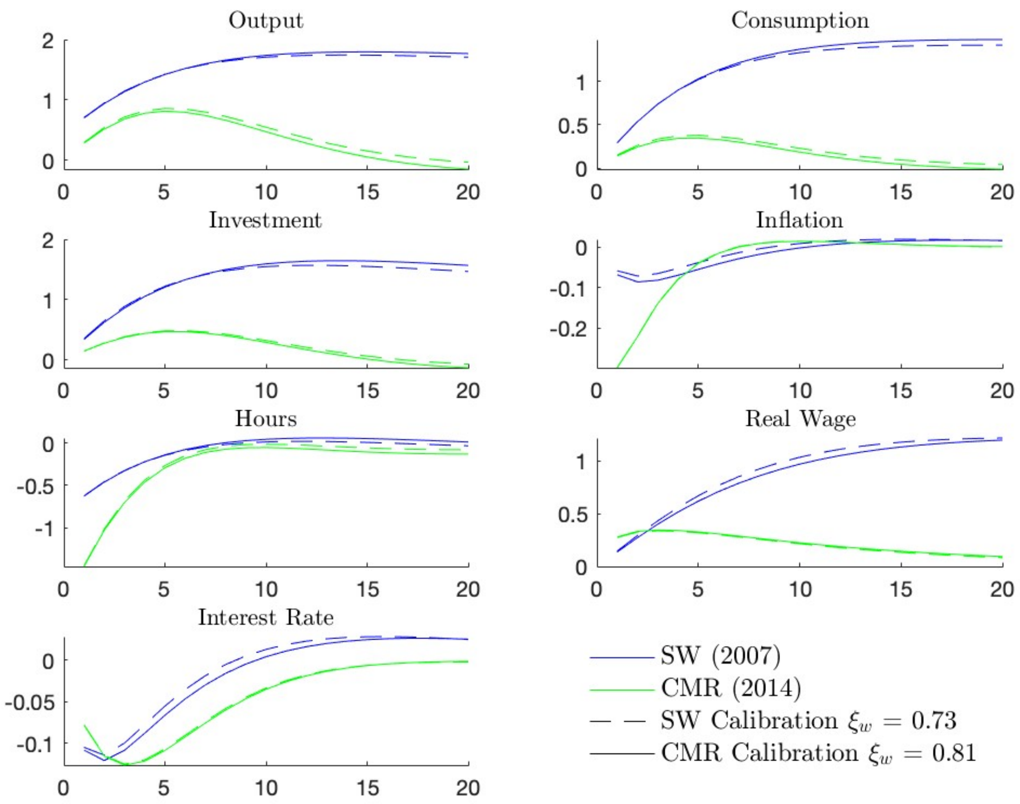

Figure A.9. Sensitivity Analysis: Calvo Parameter Wage Stickiness. Neutral Technology Shock to SW (2007), CMR (2014). Colors indicating the models: Blue: SW (2007); Green: CMR (2014). Line styles indicating calibration: Dashed line: SW Calibration ξ_w = 0.73; Solid line: CMR Calibration ξ_w = 0.81.

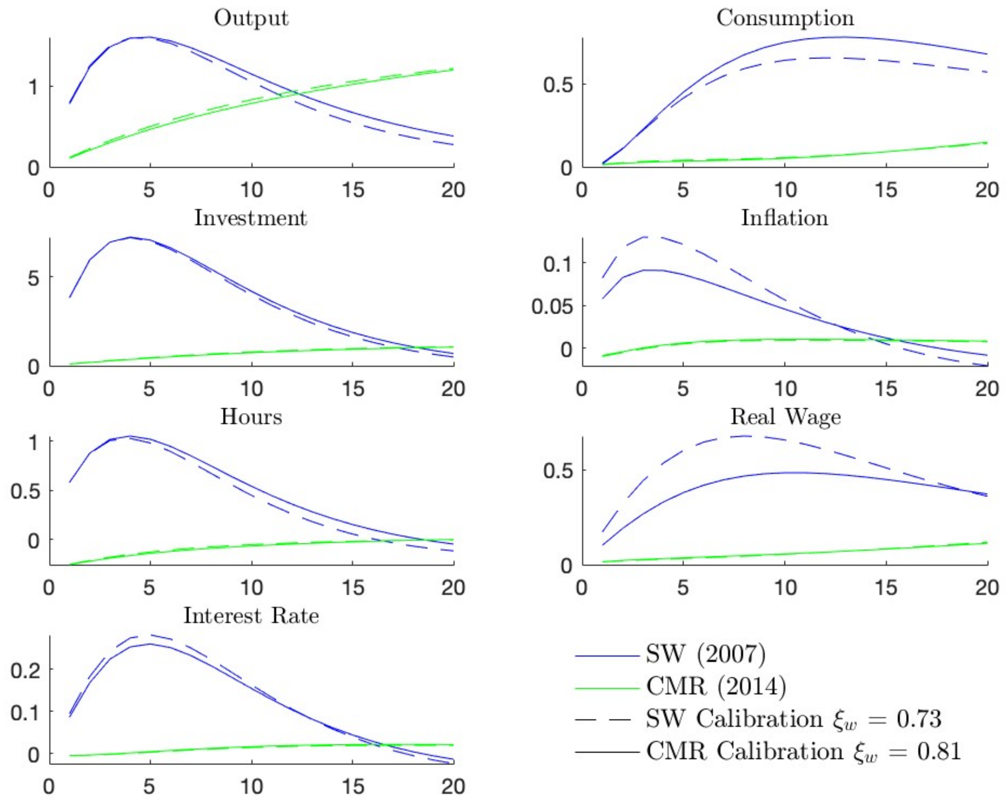

Figure A.10. Sensitivity Analysis: Calvo Parameter Wage Stickiness. Investment-specific Technology Shock to SW (2007), CMR (2014). Colors indicating the models: Blue: SW (2007); Green: CMR (2014). Line styles indicating calibration: Dashed line: SW Calibration ξ_w = 0.73; Solid line: CMR Calibration ξ_w = 0.81.

Investment Adjustment Cost Parameter

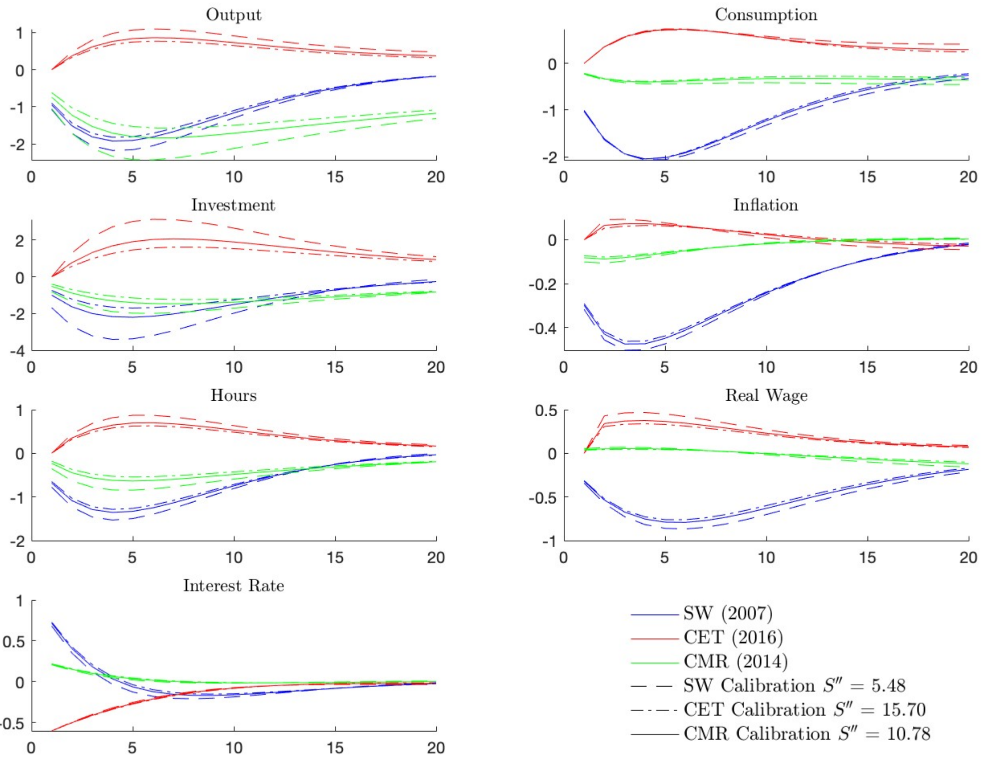

Figure A.11. Sensitivity Analysis: Investment Adjustment Cost Parameter. Monetary Policy Shock to SW (2007), CET (2016), CMR (2014). Colors indicating the models: Blue: SW (2007); Red: CET (2016); Green: CMR (2014). Line styles indicating calibration: Dashed line: SW Calibration $S'' = 5.48$; Dash-dot line: CET Calibration $S'' = 15.70$; Solid line: CMR Calibration $S'' = 10.78$.

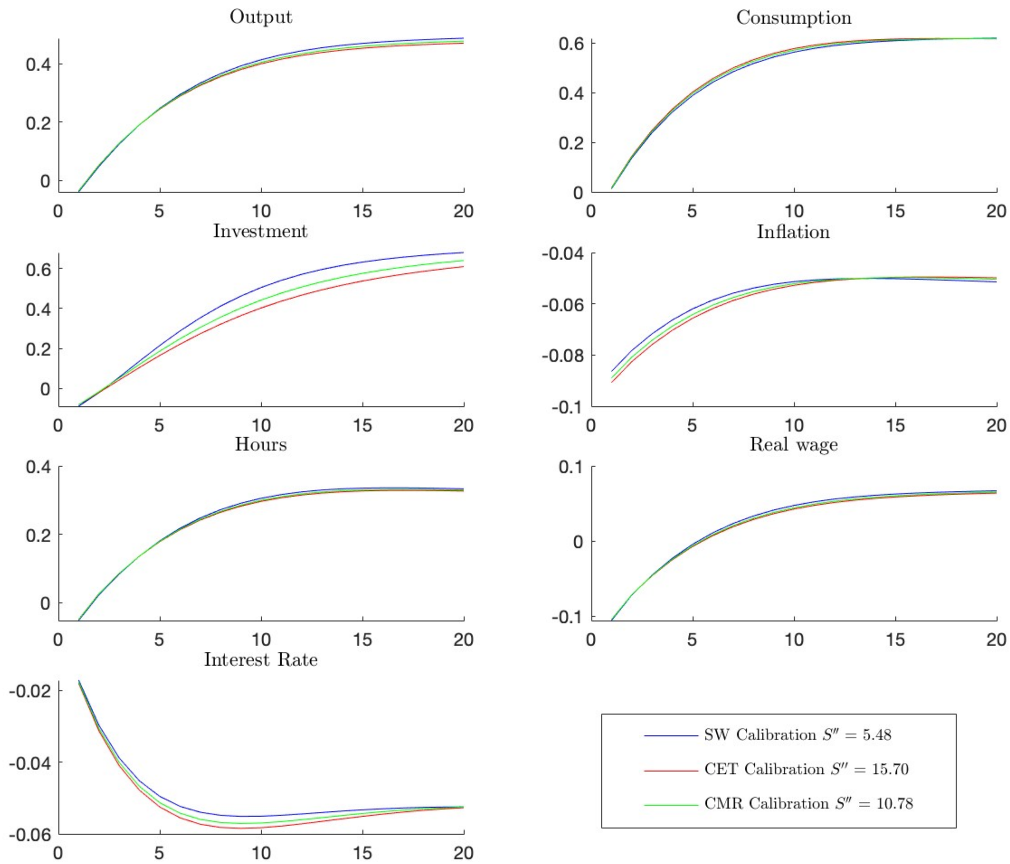

Figure A.12. Sensitivity Analysis: Investment Adjustment Cost Parameter. Neutral technology Shock to CET (2016). Colors indicating the calibration: Blue: SW Calibration S'' = 5.48; Red: CET Calibration S'' = 15.70; Green: CMR Calibration S'' = 10.78.