ESSAYS ON THE EVALUATION AND ESTIMATION OF THE HETEROGENEITY OF PRICE STICKINESS IN A DSGE MODEL

By

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A Thesis Submitted in Fulfilment of the Requirements for the Degree of Doctor of Philosophy of Cardiff University

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May 2012

To my dad and mom

Acknowledgement

Firstly, I would like to express my deeply thanks to my supervisor Prof. Huw Dixon for his continuous guidance, support and encouragement in every stage of my PhD studies. Without his supervision, I would not have reached where I am today. Special appreciation and sincere thanks to Prof. Patrick Minford for providing me the scholarship and opportunity to study in Cardiff University and also giving me valuable advice, constructive comments and inspiration during my PhD studies.

I am grateful to Herve Le Bihan for providing me with his French micro data evidence for measuring survival function of price rigidity and computational toolbox of related work in 2010. My thanks also go to Dr. David Meenagh who gave a lot of generous help on programme algorithms on indirect inference methods during my thesis writing up period. My special thanks also go to Prof. Michel Juillard for his kind helps on computational problems in Dynare.

I would also like to thank my colleagues Chunpin Liu, Hao Hong, Hongru Zhang, Jingwen Fan, Kun Tian, Li Dai, Peng Zhou, Yuqun Hong and Zhirong Ou for their valuable suggestions and discussions at various stages of this thesis.

For emotional and motivational support, I thank my best friends Jue Liu, Lucun Yang, Lu Li, Meng Xia, Wei Ye, Xinyi Zhang and Tingting Hu for their sisterhood and hearty support.

My sincere thanks are also extended to faculty and staff members, especially Ms. Elsie Phillips, Ms. Laine Clayton and Ms. Karen Jones at Cardiff Business School for their support.

Finally, I wish to thank my dad and mom who stood with me every step of the way.

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Glossary of Abbreviation

Abbreviation	*Interpretation*
CEE	Christiano, Eichenbaum, and Evans
CES	Constant Elasticity of Substitution
DSGE	Dynamic Stochastic General Equilibrium
GC	Generalised Calvo
GTE	Generalised Taylor Economy
IC	Calvo with Indexation
II	Indirect Inference
iid	identically and independently distributed
IRFs	Impulse Response Functions
NNS	New Neoclassical Synthesis
RBC	Real Business Cycle
SA	Simulated Annealing
SW	Smets and Wouters

Abstract

The ‘New Keynesian’ model assumes that prices and wages are in an extreme ‘sticky’ pattern. In this model, the assumption that a lagged indexation scheme increases the persistence of inflation is in widespread used; however, in reality, this ad hoc indexation setup is inconsistent with the real data. Moreover, there is extensive evidence on micro price data indicates that heterogeneity in price stickiness is a commonly found feature of price setting throughout the Euro area. Therefore, this thesis aims at incorporating this micro price evidence in an elaborated New Keynesian Dynamic Stochastic General Equilibrium (DSGE) model by using a Generalised-Taylor-Economy (GTE) and Generalised-Calvo (GC) price settings. This thesis first presents the models, which are an extension of Smets-Wouters (SW) model (2003) which replaces Calvo with indexation price setting with heterogeneous price settings. In these new price settings, the micro evidence of heterogeneous price stickiness is directly emerged into macro DSGE models. The findings suggest that heterogeneous price stickiness can generate long-lived inflation and output persistence. Indirect inference is then used to evaluate the DSGE models of the French economy under different price settings. The results of the testing show that all models with different price settings are comprehensively rejected. The models are then estimated with Bayesian techniques as SW (2003) by using seven key macroeconomic observables. The results show that the GC model has the best performance. The rankings of the different price setting models are also proven to be robust to different priors and observables. Indirect inference evaluations are then conducted based on Bayesian estimated models, and all models are rejected. Indirect inference is then used as an estimation method. The testing results are improved on all models. The GC model is still considered to be the best performance model among all of the different price setting models.

Chapter 1 General Introduction

1.1 General Backgrounds, Motivations and Objectives

Are prices sticky? How sticky are they? What are the implications of price stickiness? These questions have been central issues in much economic research for some time. In the view of the Classical School (see for example Pasinetti (1960), Samuelson (1978)) , the prices and wages are flexible and the market clears all the time. On the contrary, Keynesian School emphasise the failure of markets to clear because of the price and wage stickiness (see for example Malinvaud (1977), Benassy (1975)). This difference is still central to the macroeconomic debate. Several currently popular theories maintain that prices can and do change every period (see for example, the Sticky Information model of Makniw and Reis (2002), the rational inattention model of Mackowiad and Weiderholt (2009)). However, there is now a large body of evidence from price micro-data that prices and wages are sticky and might not change for many months (Baudry, Bihan et al. 2004; Bils and Klenow 2004; Álvarez, Dhyne et al. 2005). The New Classical and Real Business Cycle (hereafter RBC) schools have been merged with the New Keynesian school to form the New Neoclassical Synthesis (hereafter NNS), which has become the mainstream in macroeconomic research nowadays, at least in relation to monetary policy. Imperfect competition and short-run rigidities in prices and wages are important features in these models. Modelling these important nominal rigidity characteristics from micro foundations into the macro model had a profound influence on both monetary policy makers and theoretical researchers. These models have been used to investigate the persistence real effects of monetary policy on the economy. A significant number of previous studies (Yun 1996; Huang and Liu 1998; Rotemberg and Woodford 1999; Giannoni and Woodford 2004; Christiano, Eichenbaum et al. 2005) have indicated that nominal rigidity is one of the most important determinants of the response of inflation and output to a structural shock in an economy. There are various ways to identify nominal rigidities and different price settings have different implications. Therefore, the objective of this thesis is to identify what type of nominal rigidities can be justified, both theoretically and empirically, in macroeconomic models. Particular attention will be given to introducing the concept of a heterogeneous price stickiness that is consistent with the recent evidence of micro price data.

In theory, the NNS model assumes that there are some constraints on the flexibility of prices (Taylor 1979; Calvo 1983; Mankiw 1985; Wolman 1999). The previous literature has mainly classified the nominal rigidities into two types, one of which is modelled in a 'time-dependent' dimension while the other is modelled in a 'state-dependent' dimension. There are two standard ways to model nominal rigidity within the time-dependent setting framework, which are: Calvo contracts (Calvo 1983) and Taylor staggered overlapping contract (Taylor 1980). The Calvo contract assumes that there is a constant price reset probability, which indicates that a fixed fraction of firms can reset their price in a given period when they receive some 'signal' and that firms do not know their price duration ex ante. On the other hand, the Taylor contract assumes that wage (can also be used for price) is fixed for a certain periods and that agent knows it ex ante. In the Taylor contracts setup it is assumed that there are number of cohorts in the economy and that the number of cohorts is the same as the duration of fixed wage. In each period one cohort renews its price and it progresses over time as each cohort renews its price. So, in aggregate, all of the cohorts in the economy act in an overlapping mode. Meanwhile, within the state-dependent price-setting framework, the price strategy varies according to the state of the economy.

Unlike the time-dependent models where the decision of price changing is independent of the state of the economy, under the state-dependent models the price changing is endogenous and whether or not agents to change price is decided according to the evaluation of the cost and benefits of a price change (Dotsey, King et al. 1999; Damjanovic and Nolan 2006; Golosov and Robert E. Lucas 2007). This thesis only focuses on the time-dependent models[1].

There are ample recent literature on the performance of the current generation of the NNS model, which embraces goods and labour market imperfect competitions, and price/wage rigidities into the micro-founded Real Business Cycle models to capture the short run real variables dynamics following a monetary shock. However, some recent studies on these conventional homogeneous price/wage setting behaviours have failed to capture the dynamic features of the economy. For example, Chari, Kehoe et al. (2000) incorporate a Taylor type four-quarter price contract in the model and they found that model with this Taylor price stickiness contract failed to generate output persistence driven by monetary shock. Ascari (2000) incorporates the Taylor's wage contract into DSGE framework and reports a similar conclusion as in Chari, Kehoe et al. (2000) with Taylor price contract that it cannot capture the inflation persistence in the real effect of monetary shocks. Clarida, Gali et al. (1999), Christiano, Eichenbaum et al.(2005), Wolman (1999) and Woodford (2003) all have indicated that standard Calvo type contract fails to match empirical persistence.

More and more extensions and modifications have been developed based on the two previously mentioned basic time-dependent price/wage settings with the aim of better

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[1] Although state dependent pricing models in principle would be preferable, the time dependent price models are more tractable (see Dotsey et. al. 1999). It is interesting to explore the state-dependent model for future research.

explaining the real effect of monetary policy on the short run dynamics of the economy as well as to better mimic the real world. Calvo with indexation prices/wages settings (Yun 1996; Erceg, Henderson et al. 2000; Smets and Wouters 2003; Christiano, Eichenbaum et al. 2005; Smets and Wouters 2007) is one of the most popular price/wage settings that is based on the conventional Calvo contract and it is applied to an additional general indexation scheme; whereby, those agents who cannot re-optimise their price/wage will update using the past inflation rate. The most influential papers using this type of Calvo with indexation price and wage setting are the theoretical Dynamic Stochastic General Equilibrium (hereafter DSGE) models that were demonstrated in Smets and Wouters (2003) (hereafter SW) and Christiano, Eichenbaum et al. (2005) (hereafter CEE). These theoretical DSGE models have been found to yield the most success in capturing the stylised facts of empirical persistence that is found in the macroeconomic data.

Although SW (2003) model has succeeded in catching the main Euro macro variables at business cycle frequencies, one of the most important features of these successes relies on the Calvo with indexation price and wage setup, which has been challenged by a number of researchers. For example, Minford and Peel (2004) argued that there is no micro foundation of this ad hoc indexation scheme and this is not consistent with optimising behaviour. The other essential criticism come from Cogley and Sbordone (2008), Dixon and Kara (2010), Dixon and Le Bihan (2010), who argue that the dominant model of Calvo with Indexation is still at odds with the evidence in its prediction that prices change every period. These points of view suggest that the way to model nominal rigidity should be found elsewhere.

In addition, conventional homogenous price setting behaviour cannot explain the sophisticated real world accurately. Taylor (1999) states that ‘there is great deal of heterogeneity in wage and price setting, in fact, the data suggest that there is as much a difference between the average lengths of different types of price setting arrangements, …, One might hope that a model with homogeneous representative price or wage setting would be a good approximation to this more complex world, but most likely some degree of heterogeneity will be required to describe reality accurately’, as the availability of the individual price data used to compute consumer price indices which is made by national statistics officers, more and more recent empirical research on micro price stickiness (Bils and Klenow 2004; Álvarez, Dhyne et al. 2005; Dhyne, Álvarez et al. 2005; Altissimo, Ehrmann et al. 2006; Nakamura and Steinsson 2008) report that the frequencies of price adjustment are significantly different across sectors.

Dixon and Kara (2005) introduced this heterogeneity of nominal stickiness concept into the Taylor price/wage setting in order to incorporate the micro data evidence directly into the price/wage setting models. They named this new model the Generalised Taylor Economy (hereafter GTE), which has many different sectors in the economy and each sector has its own fixed prices/wages setting periods. Moreover, Carvalho (2006) considers a Multiple Calvo (hereafter MC) price setting, which has multiple sectors in the economy, each with a sector-specific Calvo type reset probability. In addition, Wolman (1999), Dixon (2010)，and Dixon and Le Bihan (2010) developed the Generalised Calvo (hereafter GC), where the Calvo reset probability is no longer a constant number but varies with the duration of contracts. Although these three main heterogeneous price and wage stickiness models have different forms to measure the nominal rigidities, they all share the same steady state distribution of price/wage stickiness (Dixon 2010). All of these works have shown that a heterogeneous price or wage setup can better explain the inflation inertia and output persistence than the conventional homogeneous Calvo and Taylor price setup.

On account of the better performance of the heterogeneity concept in modelling nominal rigidity and the critiques of SW model which use the ad hoc indexation scheme in a Calvo type contract which are found in the previous literature, the first motivation of this thesis is to introduce the heterogeneity in price stickiness[2] into macro DSGE model. It uses the French micro price data which is collected by Baudry, Bihan et al.(2007) and calibrated by Dixon and Le Bihan (2010) and applied the GTE and GC price setting structures in the fully specified SW (2003) to be compared with SW (2003) benchmark Calvo with Indexation price setup as well as the conventional homogeneous Calvo and Taylor price setups. There are total five models analysed in this thesis which only differ in the price setting behaviour, rest structure of the model is left as it is. The first objective of this thesis is to see whether these heterogeneous price setting models can better replicate the stylised fact of empirical persistence found in macroeconomic data than homogeneous alternatives by using Dynare software (Adjemian, Bastani et al. 2011) to carry out model simulations.

Although SW (2003, 2007) report their success in using the DSGE model in fitting the dynamic properties of the main macro Euro and U.S. data compared with a Bayesian and a standard VAR, Meenagh, Minford et al.(2008) and Le, Meenagh et al.(2008) have indicated that both of the SW models for the Euro and U.S. economy are rejected by using a new evaluation method, which is called 'indirect inference'. This new method exploits the properties of the structural model's error processes through bootstrap simulations. It looks at whether the simulated data from the calibrated or estimated structural model can explain the real data by using an

[2] Because of the lack of wage micro data evidence, this thesis only focuses on investigating the heterogeneity in price stickiness. Heterogeneity in wage stickiness will be of interest to future research.

independent auxiliary model, such as a VAR, to measure the dynamic behaviour of the data. A Wald test is used in this method to measure the overall capacity of the structural model to fit the data. By using a Wald statistic, this test establishes whether or not the parameters of a time-series representation estimated on the actual data lie within some confidence interval of the model-implies distribution. In the studies by Meenagh, Minford et al.(2008) and Le, Meenagh et al.(2008) the SW (2003, 2007) models are strongly rejected because of their failure to fit the dynamic properties of the data and generate excessive variance compared with the real data. They also indicate that the properties of the prior distribution of the parameters and the stochastic shocks are key elements in the success of SW models.

In view of the sufficient explanatory power of heterogeneous GTE and GC price settings which are demonstrated in the previous relevant literature (Wolman 1999; Carvalho 2006; Jiang 2009; Dixon and Kara 2010), the second motivation of this thesis is to adopt the so-called 'indirect inference' evaluation method that was developed by Minford, Theodoridis et al. (2007) in testing and comparing the explanatory power of the SW (2003) models with various price settings for the French economy. The second objective of this thesis is to using the French macro quarterly data from 1978 to 2010 together with the micro French price data evidence (Dixon and Le Bihan 2010) with Indirect Inference method to test whether heterogeneous price setting model can replicate the dynamic features of the data. The testing results can also be used to confirm the simulation results that are analysed in Chapter 2.

The indirect inference testing procedure in Chapter 3 is using the consensus calibrations in the literature (Smets and Wouters 2003; Smets and Wouters 2007) that pin down the structure of the economy so that if those calibrated parameters are assumed to be true then they would be able to identify the marginal contribution of the different ways to measure price rigidities since the five models only differs in the price setting behaviour. However, since fixing the model parameter is a strong assumption to testing and comparing DSGE models, it cannot be inferred that one model rejected in this set of parameters will be rejected by another set of reasonable parameters. This can be explained as the model is rejected not because of an incorrect way to measure the price setting behaviour but because the other frictions in the model have failed to reflect the true structure of the economy. Thus, the third motivation of this thesis is that the models should be fully estimated in order to find the best set of parameters by searching over the full range of potential values of the models before they are evaluated and compared with each other.

Various macroeconometric techniques are developed to estimate the DSGE models along with the development of modelling. The Bayesian estimation method is a strong econometric estimation method which is quite popular in current economic research, which is based on the whole theoretical models' performance. The key element which distinguishes Bayesian estimation from the classical maximum likelihood estimation method is the use of priors. The advantage of using priors is it can link the previously useful literature into account and it can also help to lessen the identification problems in estimating DSGE models. Moreover, Bayes factor provide an easy way to relatively evaluate the performance of models. Thus, the third objective of this thesis is to use the Bayesian estimation method, which is the same technique as SW (2003), to estimate the different homogeneous and heterogeneous price setting models. Through using the rule of Bayes Factors and comparing the log marginal likelihood of these five variant models, the overall performance of different price setting models can be compared and ranked in a relative way.

There is no absolute best way to choose macroeconometric methods to estimate and evaluate models. Although the incorporation of priors has its advantages compared with the classical method, the most challenge of this incorporation of prior is these prior distributions put ‘restrictions’ before estimation. In addition, how to set prior distributions before estimation is still a point of debate in current research. Besides that, although Bayes factor provides an easy way to do relative model comparison, it cannot test whether an individual model itself is verified by the real data in the absolute sense. Thus, the fourth motivation of this thesis is to use an ‘unrestricted’ estimation and evaluation method, indirect inference, to estimate different price setting models. The way to distinguish indirect inference estimation from the Bayesian approach is through the use of an auxiliary model that is completely independent of the theory to generate descriptors of the data against which the theoretical model is indirectly estimated. The difference between indirect inference estimation and the previously used indirect inference evaluation is that the aim of indirect inference testing is to calculate the Wald statistics to see whether or not the theory can generate the true data when the structural parameters are given, while the purpose of indirect inference estimation is to find the best set of parameters based on the real data that are close enough to the mean of the Wald statistics distribution from model simulations. The fourth objective of this thesis is to estimate different price setting models using indirect inference which is used as a robust check of the results in the previous findings.

1.2 Outlines and Contributions

This thesis includes four main analyses, which are demonstrated from Chapter 2 to Chapter 5. The brief descriptions of the outlines and contributions of each chapter are demonstrated as follows:

Chapter 2 first reviews the recent literature on the performance of NNS models with different price/wage rigidity behaviours to capture the stylised fact of Business Cycle statistics. By introducing the French micro price data evidence (Dixon and Le Bihan 2010) into GTE and GC price setting model, and applying the corresponding average frequency of price adjustment and fixed duration of price contract into conventional Calvo and Taylor price settings, the main findings in Chapter 2 reveal that the models with heterogeneity in price stickiness are relatively superior to the homogenous price settings. In particular, GTE price setting tends to have a longer tail in the impulse response of inflation to monetary policy shock and GC tends to have more persistence effect in output following a monetary policy shock. In addition, GTE is the only model to catch the feature that the response of inflation will be more delayed than that of output. The intuition is that with the introduction of heterogeneity in price stickiness, the presence of more sticky sectors or longer contracts are taken into consideration can dampen the effects on the response of those sectors or contracts with less stickiness to a monetary policy shock. Turning to the homogenous price setting models, the ad hoc indexation scheme to past inflation cannot improve the persistence measure of Calvo type contract, this finding is in line with SW (2007). The simple Taylor price setting behaves worst among the five price setting candidates. The intuition behind this is Taylor type price setting model fix the price ex ante which result in a less forward looking compared with Calvo type contract.

In Chapter 3, indirect inference (which is first introduced by Meenagh, Minford et al.(2008)) is used as a testing method to evaluate the calibrated models under different price settings. This test establishes, using a Wald statistic, whether the parameters of a time-series representation estimated on the actual data lie within some confidence interval of the model-implies distribution. Neither the homogeneous price stickiness DSGE model nor the heterogeneous price stickiness DSGE models are all rejected when the whole set of macro variables (including output, inflation, interest rate, consumption and investment) are taken into consideration. One of the reasons for the rejection may be the inaccurate measurement in consumption and investment, which cannot pick up the fine details of the GDP components. However, the results are worth highlighting when the views move to the main macro variables (i.e. output, inflation and interest rates) which are of key interest for policy makers: all homogeneous price settings, Calvo with indexation, simple Calvo and Taylor respectively, are all rejected at 95% confidence level; and the heterogeneous GTE price setting model is on the border of rejection at 5% significance level. The key point that comes out of all of the evaluation of the results is that the GC price setting model is the only model that can convincingly encompass the behaviour of the French economy on output, inflation and interest rates, which is by a considerable degree the closest to the data. The results in Chapter 3 suggest that the heterogeneous GTE and GC price setting models can provide better explanations to both the dynamics and the volatilities of real data than Calvo with indexation price setting as well as conventional Calvo and Taylor price settings.

Having compared the different price setting models' capacity in mimicking the dynamics and volatility of the real data, Chapter 3 has shown that the heterogeneous price setting model is superior to conventional homogeneous price setting alternatives in representing the French economy during the period from 1978 to 2010. Although the evaluation results in Chapter 3 demonstrate that heterogeneous price setting models can fit the data better than homogenous models, the calibrated model which takes the whole set of macro variables into consideration are all rejected, even at the more tolerant 99% confidence level. One possibility why these models fail the indirect inference testing procedure is because of the model misspecification problem. The inappropriate calibrated values of structure parameters of the models could be another possibility. In order to make evaluation more robust, model estimation should be taken first.

In Chapter 4, Bayesian technique is applied to estimate these different price setting models. The starting point of prior distributions of structural parameters is the same as in SW (2003), which is chosen to have large variances and thus guarantee that the prior distributions cover a wide range of parameter values. The Bayesian econometric approach can not only do model estimation but it can also be used for model comparison. Marginal likelihood measures the prediction performance of the model and the Bayes Factor can be used as a relative measure of model comparison to find the most useful model with least overall misspecification. The results strongly favour GC since the GC price setting model yields the least log data density relative to the other four models. Different parameters' prior distributions, as well as different observables, are used in the robustness check; however, the relative ranking of these different price-setting models has not changed.

The indirect inference evaluation method is then applied on those Bayesian estimated models; all of which are again rejected. Chapter 5 is an extension of Chapter 3, which uses indirect inference as an 'unrestricted' estimation method by using the total information from the sample to estimate the whole model and then precede the testing procedure on previously estimated models. The results have been improved for all models, even though they still fail to pass the test at the 95% confidence level when all main macro variables are taken into consideration. Different combinations of variables have been tried and the GC price setting model is the best when compared with the other four price setting models. GTE yields the second best outcome, which indicates that the heterogeneous price stickiness can better replicate the data behaviour than the homogeneous price setting models.

In this thesis two different estimation and evaluation methods have been applied in the different price setting models. To summarise, the main contribution of this thesis is to compare both heterogeneous and homogeneous price setting models using different econometric approaches to investigate the most useful and appropriate way to measure nominal price rigidities which is not fully analysed in the previous studies. Each econometric method has its own focus on the questions to be solved; for example, in the Bayesian estimation method the criterion is to use the likelihood of the data and to find how small the current period forecast error is. In addition, priors are used and can be considered as a belief or a restriction before the estimation is made. When using a Bayesian estimation method, the estimated results show that the GC model is the best in terms of marginal likelihood; however, although the Bayesian estimates are the 'best given the priors', they do not test the overall performance of the model against the data but only give the relative ranking among different price setting models. While in indirect inference estimation, the criterion is to use the likelihood of the data behaviour and to find how close the VAR coefficients are. Since the auxiliary model is chosen in VAR(1) form, which can be considered as a theory-free way to measure the economic relationship, by using the simulated annealing algorithm it is able to find the set of structural parameters that give the global minimum 'Wald statistics' in an unrestricted way. The indirect inference estimation and testing process has strong power against a false model, as shown in Le, Minford et al. (2010). This result can also confirm the conclusion drawn in Bayesian estimation results of the superiority of GC price setting model to fit the facts of the French economy.

All in all, different approaches have different criteria and implications. Which econometric methods to use and which ways to measure nominal rigidity depend on the questions need to solve as well as the interests for policy makers. From these results by using two different estimation methods, GC price setting model is found to be the only one model that is the best fitting to either the data or the data behaviour. GTE is the second best model to fit the data behaviour and it is the only model can generate the hump-shaped inflation and output persistence as well as to fit the empirical feature of co-movement of inflation and output. Overall, these heterogeneous price setting models have significantly improved the models' explanatory power and prediction performance. These results prove the empirical validity and reliability of the incorporation of heterogeneity of price stickiness in New Keynesian DSGE model.

Chapter 2 Nominal Rigidity in DSGE Model

2.1 Introduction

The study of nominal rigidity in the DSGE model is currently a central concern of much economic research. The NNS models have now become the mainstream in macroeconomic research, which combines the Classical school of economics with Keynesian features. Imperfect competition and short-run rigidities in price and wage are fairly important features in these models. There are two main categories to characterise nominal rigidity, the first is time-dependent price setting rules and the second is state-dependent price setting strategy. Modelling these important characteristics from micro foundations into the macro model has been widely used to investigate the persistence of the real effects of monetary policy on the economy.

The main context for this thesis is the influential study by CEE (2005) and SW (2003) who have developed DSGE models for the U.S. and Euro area economies. These models have been designed to reveal the empirical properties of U.S. and Euro area data in a way that is consistent with New Keynesian theory. In order to capture the business cycle fluctuations in the real data, these models incorporate a number of real rigidities such as external habit formation in consumption and variable capital utilisation etc. and many of these settings have become standard in the DSGE literature. For example, Greenwood, Hercowitz and Huffmann (1988) incorporate the endogenous capital utilisation of installed capital into a neoclassical framework and found that this feature may be an important element to explain business cycles since it helps to prevent the sharp change in marginal costs after a monetary policy shock. King and Rebelo(2000) then modelled the capital depreciation as an increasing function of the variable utilisation rate, which helps to smooth the adjustment of the rental rate of capital in response to changes in output. The cost of adjusting capital stock is modelled as a function of the change in investment followed by CEE (2005) in order to help explain investment volatility. Meanwhile, external habit formation in consumption is used to give the necessary empirical persistence in the consumption process.

In addition to the incorporation of these real rigidities to help improve the model's performance, the other key element in this DSGE model to explain output and inflation persistence is the Calvo price and wage setting with partial indexation. In this type of price and wage settings, firms (households) have a constant probability to be able to optimally reset prices (wages), for those firms (households) who cannot optimally reset prices (wages) the nominal prices (wages) are automatically updated with past inflation.

Moreover, there are ten structural shocks involved in the DSGE model: two 'supply' shocks (productivity shock and labour shock); three 'demand' shocks (preference shock, investment adjustment cost function shock, and government expenditure shock); three 'cost-push' shocks (price markup shock, wage markup shock, and risk premium on capital shock); two monetary policy shock (inflation targeting shock and interest rate shock). The full set of structure shocks are used for deep investigation of the effects of each shock and of their contributions to business cycle fluctuations.

In SW (2003), this DSGE model is estimated using Bayesian estimation techniques with seven macro observable time series. The results show that the estimated DSGE model is performing well to capture the dynamic and volatility in the real data of the Euro area. The effects of ten orthogonal structure shocks included in the models are also qualitatively consistent with the existing evidence in the Euro area. A temporary rise in the nominal and real interest rate leads to a hump-shaped fall in both output, consumption, and inflation (Smets and Peersman 2001). Similarly, a positive productivity shock leads to a gradual increase in output, consumption, investment and the real wage, but has a negative effect on employment (Gali 1999). Unlike the well-known property of calibrated RBC models driven by technology shocks shows that a high positive correlation between labour productivity and employment (Christiano, Eichenbaum et al. 2003), Gali (1999) reports a countercyclical co-movement between productivity and employment, which is usually detected in the real data. He argues that in equilibrium, aggregate demand is determined by the level of aggregate real balances. With price stickiness and limited monetary accommodation, the short-run response to a positive productivity shock is associated with little or no change in the real money supply. Accordingly, the increase in aggregate demand will fall short of the increase in multifactor productivity, inducing firms to decrease correlation between employment and productivity. This finding is also shown in recent literatures (Francis and Ramey 2002; Gali, Lopez-Salido et al. 2003; Basu, Fernald et al. 2004; Uhlig 2004; Collard and Dellas 2007). The marginal cost falls in turn influence inflation to decrease gradually due to the rise in productivity. Estimation results also report high price stickiness in the Euro area and the price and wage stickiness are found to be equally important to capture the impulse responses following a monetary policy shock.

SW (2003) is successful in capturing the real business cycle properties, one of the most important features to improve model performance is the Calvo with indexation price setting, which is defined as firms have a constant reset probability to be able to optimally reset price and when firms do not optimally reset prices the nominal price is automatically updated in response to inflation. However, Dixon and Le Bihan (2010) who argue that this price setting approach is at odds with the evidence of the real micro data (Cogley and Sbordone 2008; Dixon and Kara 2010). In addition, the other motivation to extend this standard benchmark model is that there is a growing amount of recent research which has studied the micro price data evidence (Bils and Klenow 2004; Álvarez, Dhyne et al. 2005; Dhyne, Álvarez et al. 2005; Altissimo, Ehrmann et al. 2006; Nakamura and Steinsson 2008). These previous studies show that the frequency of price adjustments differs substantially across sectors. Introducing micro data evidence of heterogeneity in price stickiness into the pricing model seems a better way to mimic the real sophisticated world. Under this purpose, the GC and also GTE price settings (Dixon 2010) are used to compare the performance of the Calvo with Indexation price setup as well as conventional simple Calvo and Taylor price settings.

The aim in this chapter is to replace the Calvo with Indexation price setting in the SW (2003) framework with heterogeneous micro-data based pricing rules as well as the conventional homogeneous Calvo and Taylor price contracts. Their ability to fit the real empirical features will then be compared. The main departure of this chapter is to merge the micro price data directly into the macro price setting DSGE models. The crucial point to understand and calibrate these micro-data based price settings is the aggregate distribution of durations of price spells. In steady state, they can be represented in two different ways: the hazard profile and the cross-sectional distribution of completed spells. The hazard profile is taken to calibrate the GC model with duration-dependent reset probabilities. The longer the price duration, the higher the probability it will be reset. The cross-sectional distribution of completed spells is used to calibrate the GTE in which there are several sectors and each with a simple

Taylor contract whose contract length differs across sectors. The aggregate shares of sectors in the economy equal to one. Each of the two models exactly reflects the same steady state distribution of durations that is revealed by the micro-data. GC captures the heterogeneous price stickiness across price-durations while GTE features it across sectors. This chapter aims at contributing to the present understanding by extending a widely applied DSGE model (Smets and Wouters, 2003) with heterogeneous price settings that directly incorporate the micro CPI data of the French economy (Dixon and Le Bihan 2010), which can facilitate the understanding of the dynamics and volatility of the economy being explained by different heterogeneous price rigidities models.

This chapter will be structured as follows. Section 2.2 will conduct a brief literature review on nominal rigidity and their implications in macro monetary policy analysis. This review will cover the recent literature on the strength and limitations of different price and wage rigidity settings to explain the real business cycle phenomenon. The model based on the different price and wage rigidity settings is presented in Section 2.3. The micro price data evidence which is used to calibrate the heterogeneity of price stickiness is reported in Section 2.4. The results, analysis, and discussion are conducted in Section 2.5, while Section 2.6 concludes the chapter.

2.2 Literature Review

The main feature of NNS models is the inclusion of monopolistic goods/labour market with differentiated intermediate firms/labour. The essence of this approach is that in the long-run all prices/wages are perfectly flexible but in the short-run prices/wages are rigid. Agents are considered as price-setters in the model's setup in order to understand the sluggish adjustment in prices/wages in the short-run, which serves as the micro foundation for Keynesian features. The NNS model obtains the effect of money on output via long lasting nominal rigidities of price/wage contracts which cause distortions in the markets. 'Contract Multiplier' can be used to demonstrate the staggering mechanism which shows that the price setters have interacted with each other. Firms set a price while taking the decisions of other firms into consideration. Therefore, each contract is written relative to other contracts, which then causes shocks to be passed on from one contract to another. The differences of price/wage strategy lead to very different predictions of the effects of monetary policy. Overall, NNS suggests that monetary policy is important to the real economy, which is persistent over time due to the gradual adjustment of individual prices and, therefore, the general price level.

2.2.1 The Characteristics of New Keynesian Models

There are two widely used time-dependent mechanisms to measure rigidities in theoretical models: the Taylor model and the Calvo model. Taylor (1979) developed the nominal wage setting model, in which all wages contracts have a fixed period duration and agents know it ex ante. The wage contracts are in a staggered pattern, which means that all contract decisions in the economy are not made at the same point in time. A wage contract is set in each period, and the contracts which are set in the previous period still have effect in the current contract period. This overlapping style determines that the wage rates set in the current period will reflect the wage rates set in previous and future contracts. Therefore, each contract is written relative to other contracts, and this causes shocks to be passed on from one contract to another (i.e. a contract multiplier). A contract multiplier causes business cycles to persist beyond the length of the longest contract. Persistence of inflation is also generated by the contract (Taylor 1980). This original wage rigidity setup can also be used for price settings.

An alternative way to modelling partial price adjustment is a Calvo (1983) type contract, which is based on a constant hazard rate model. In each period, the agent faces a constant probability of resetting price when he receives a random signal. When the agent sets his price he takes into account the infinite horizon and the probability of current price which is still being in force will also be taken into consideration for future price setups. Usually the reset probability diminishes as the price last longer. Although firms choose an optimal price in a dynamic setting, the fundamental probability of resetting price is not explained. This price setting behaviour can also apply to households, who reset their wages. The price and wage setting means that there is a distribution of firms' prices and households' wages since some firms and households have more chance to change their price while some may never have a chance, which will be exhibited in the tails of the distribution. The bigger the distribution is then the more the dispersion will be and the more inefficiency there is in the economy.

The traditional way to link the Calvo reset probability and Taylor fixed contact duration is defined that expected duration of contract is equal to the reciprocal of the reset probability. If the reset probability is ¼ per quarter, which means that it will be 25% of firms resetting price in any one quarter. When it sets its price, each firm expects that the price setting will last for four quarters. Kiley (2002) compares these two nominal price rigidity specifications (i.e. Taylor and Calvo price settings) in a small optimizing IS/LM model and finds that the dynamics are both qualitatively and quantitatively different across these two pricing specifications when the models are calibrated with identical average frequencies of price adjustment, which contradicts the overwhelming perception in the literature that these two price specifications imply similar dynamics, at least in the reduced-form models (Roberts 1995; Dotsey, King et al. 1999; Galí and Gertler 1999; Taylor 1999; Zhou and Zhang 2011). Kiley (2002) argues that, qualitatively, the degree of relative price dispersion between the different price adjustments models are quite large, in the Calvo model, the relative price dispersion is much greater than that implied by a Taylor model with the same average frequency of price adjustment because of the more forward-looking nature of the Calvo model. In addition, it also shows that a model with Calvo partial price adjustment setups can generate more persistence to output fluctuation compared with Taylor staggering price specification because the small fraction of price setters who do not adjust price frequently lead to a more sluggish responses of prices than a Taylor contract with the same average frequency of price adjustment.

The two key parameters to measure the nominal rigidity in the time-dependent models are the reset probability (which is used in Calvo setups) and the length of fixed contract (which is used in the Taylor setups); however, these two key parameters are easily confused when comparing models. Dixon and Kara (2006) point out that three criteria should first be clarified in order to make a comparison between Calvo and Taylor contracts, they are: firstly, the average length of completed contracts; secondly, the average age of contracts (including the uncompleted contracts); and finally, the average frequency of price adjustment. Using these different criterions will give a different measure of nominal rigidity. The average length of completed contracts is approximately twice as the average age of contracts in both Calvo and Taylor setups[3]. Dixon and Kara (2006) point out that most researchers (i.e. Kiley, 2002) have wrongly compared the average age of Calvo contracts with the average length of

[3] Details see Dixon and Kara (2006)

completed contracts, which gives the inconsistent measure of nominal rigidity thus trigger almost 100% off in order of magnitude. Although Kiley (2002) chooses the wrong parameterisation to compare the two models, qualitatively there is a difference between these two pricing specifications. Dixon and Kara (2006) have found that the Calvo model still generates more output persistent than the Taylor model but with quantitatively less marked difference. The reason for this is demonstrated by Dixon and Kara (2005) who found that the presence of long contracts in Calvo model setups can lead to more persistence and price dispersion.

2.2.2 The Performance of NNS Models

The aim of NNS models is to fit the 'dynamic facts' of the economy, in particular the impacts of monetary shocks to the real economy. One of the ways to measure the model's performance is to look at the model's ability to generate the persistence that is observed in the data. It is widely agreed that inflation and output have a delayed a hump-shaped response to monetary policy. For example, Christiano, Eichenbaum et al. (2005) found that after an expansionary monetary policy shock there is a hump-shaped response of output, consumption and investment, with the peak effect occurs after about 1.5 years; there is a hump-shaped response of inflation with peak response after about 2 years, which is followed by a fall in the interest rate for roughly 1 year.

Different researchers have estimated different responses of main macro variables to monetary policy shocks by using different price setting models. For example, Rotemberg and Woodford (1999) use a Calvo partial price adjustment contract to examine output persistence to monetary shocks and they find that the Calvo price contract can successfully generate output persistence. Chari, Kehoe and McGrattan

(2000) studied a DSGE model with a standard Taylor price-staggering (1980) to examine whether or not the model can generate a monetary business cycle. The standard Taylor type sticky price model is used and real money balances enter the consumer's utility functions, there is also capital accumulation. The results show that this model with fixed four-period of exogenous price stickiness fails to generate the output persistence driven by monetary shocks. In Chari, Kehoe and McGrattan (2000), the effect of staggered price-setting on the persistence of output is measured by the contract multiplier, which is the ratio of the half-life of output deviations after a monetary shock with staggered price-setting to the corresponding half-life with synchronised price-setting. The length of synchronised price setting is roughly one-half the length of exogenous price stickiness. In this paper, the half-life of output deviations in the data is ten quarters and the period of exogenous price stickiness is about one quarter. In order to match the data the model with staggered price-setting it must produce a contract multiplier of about twenty; however, the calibration's contract multiplier is only one. Therefore, the benchmark model with only four-period staggered price setting does not generate persistence because the elasticity of the short-run aggregate supply curve is quite large, so that monetary shocks induce firms to adjust to raise their prices even more than they would in flexible-price equilibrium. Thus, Chari, Kehoe and McGrattan (2000) conclude that the way to determine the output persistence should be found elsewhere. Mankiw and Reis (2002) argue that the failure of the price stickiness model to produce plausible inflation and output dynamics following a monetary shock is caused by a rapid change in the inflation rate. For solving this persistence puzzle, other works related to non-constant elasticity of substitution (non-CES) production function and factor specificity to a staggered price model are used to help to generate persistence (Bergin and Feenstra 2000).

In addition to the extensive studies of price sluggishness in New Keynesian models, considerable attention has been given to nominal wages stickiness. Some researchers emphasise that wage rigidity is more important than price rigidity in explaining the stylised facts. For example, Huang and Liu (1998) argue that wage stickiness is more important than price stickiness for generating output persistence. In Huang and Liu (1998), the Taylor type staggered wage contract rather than the staggered price contract (as in Chari, Kehoe and McGrattan (2000)) is incorporated in the model and they found that staggered wage contracts are an important contributing mechanism in generating persistent real effects of monetary policy shocks and they also found that adding staggered price mechanism on the staggered wage model cannot help to magnify persistence. However, Ascari (2000) incorporates Taylor's staggered wage setting model into an DSGE framework and reports a similar conclusion as in Chari, Kehoe and McGrattan (2000) who use a Taylor type price setting framework that the nominal rigidity model cannot capture the inflation persistence in the real effect of money shocks. However, Dixon and Kara (2006) show that the Taylor type staggered wage contract model can generate the hump-shape impulse response of inflation persistence while the other type of nominal wage rigidity of the Calvo contract type itself does not generate hump-shaped inflation response to monetary disturbances, which might be due to the purely forward-looking nature of the Calvo model.

Nominal rigidities in both wage and price are now commonly used (Erceg, Henderson et al. 2000; Smets and Wouters 2003; Christiano, Eichenbaum et al. 2005; Smets and Wouters 2007). Christiano, Eichenbaum et al. (2005) estimate a model with both price and wage stickiness using U.S. data and report that wage rigidity and not price rigidity is the key to accounting for the observed dynamics of inflation and output. However, Smets and Wouters (2007) report that price and wage stickiness are equally important in the set-up. In addition, Goodfriend and King (2001) argue that although nominal wages are sticky, the long-term nature of employment relationships means that nominal wage rigidity has little implication for real resource allocation. The labour market is characterised by long-term relationships where there are opportunities and reasons for firms and workers to neutralise the allocative effect of temporarily sticky nominal wages. The product market is characterised by spot transactions where there is less opportunity for the effects of sticky nominal prices to be privately neutralised. Therefore, the consequences of temporary nominal wage rigidity are likely to be minor, but temporarily sticky nominal product prices can influence the average mark-up significantly over time. Woodford (2003) came to a similar conclusion about the necessity for excluding wage stickiness in the NNS model. He says that if researchers are only interested in constructing a positive model of the co-movement of inflation and output, and then given the way that both can be affected by monetary policy, wage stickiness does not matter because it only flattens the short run Phillips curve further compared with price stickiness. The same effects in wage stickiness can be achieved by manipulating the values of other coefficients under the flexible wage model.

Based on the conventional time-dependent price/wage setting models, there are other modifications to improve the New Keynesian model's performance. Yun (1996) assumes that prices which cannot optimally reset are automatically increased with the average inflation and shows that this price rigid settings performs better than flexible price settings to explain the co-movement of inflation and output. This modification of the Calvo model to link with past inflation can help to eliminate the quickly changing effect of the inflation rate. Ireland (2004) proposes another way to extend the simple Calvo model by introducing the Central Bank's inflation target and then comparing the empirical performance of this model with Calvo with full indexation, and concludes that the Central Bank's inflation target performs better than the Calvo with indexation model. Also Dixon and Kara (2006) explore the Calvo with Indexation model, which adds an ad hoc indexation scheme to the Calvo model in which the contract duration who cannot reoptimise is updated with lagged inflation. Although this justification helps to improve a hump-shaped response of inflation persistence to monetary shock, Dixon and Kara (2010) point out that this ad hoc extension to Calvo contract fails to fit the micro data.

Christiano, Eichenbaum et al. (2005), and Smets and Wouters (2003)—typically contain real rigidities alongside the nominal rigidities. Both of these studies assume partial and full indexation in both wages and prices settings and argue that this extension of the Calvo model improves the empirical fit of their models because the allowance for backward-looking indexation generates the New Keynesian Phillips Curve where the inflation rate is not only a purely forward looking function of the expected path of the output gap but also depends on the previous period's inflation rate. Therefore, this extension implies that inflation inertia is greater as the indexation parameter is larger. Unlike Calvo price/wage setting with partial indexation in SW (2003), CEE (2005) extend a model with full indexation and show that it can better fit the estimated impulse response than the standard non-index model. In SW (2003) the indexation parameters for price and wages are treated as free parameters and they report that their model fits the data well when there are 64% and 42% of prices and wages being indexed to lagged inflation. These results are considered to be the most empirically successful variant of the New Keynesian model.

Giannoni and Woodford (2004) also treat this indexation parameter as a free parameter, but find that full indexation is the best scheme to use. These authors find that a model with staggered wage-setting as well as staggered price-setting and automatic indexation of both wages and prices to recent past inflation can account fairly well for the joint dynamics of wages, prices and real activity. However, Smets and Wouters (2007) estimate a model based on CEE (2005) on U.S. data covering the period 1966Q1 to 2004Q4 and they find that backward looking inflation indexation is relatively unimportant in both goods and labour markets. The marginal likelihood of the estimation improves with very low values of price indexation, which means it would be better to leave this friction out. Moreover, leaving out either wage or price indexation does not make any impact on the other parameters. Laforte (2007) draws a similar conclusion that incorporating the indexation in the New Keynesian model is a poor way to match the inflation process in the U.S. economy.

2.2.3 Micro Data Evidence of the Heterogeneity of Price Stickiness

Recently more and more studies have focused on incorporating the micro data evidence into macro models, especially with the introduction of heterogeneity in price stickiness. For example, Taylor (1999) states that there is a great deal of heterogeneity in wage and price setting. A model with homogenous representative price/wage setting would not be able to approximate the more complex world accurately.

As the individual price data which is used to compute consumer price indices has become available to researchers a considerable body of research has emerged on micro price evidence and nominal rigidities. The first comprehensive study on price changes and its implications was published by Bils and Klenow (2004), who investigate the average frequency of price adjustment in 360 categories of consumption goods in the U.S. during 1995-1997. Their findings show that the average duration of different product and service categories have profound differences among the 360 categories. Based on this finding, a multi-sector model with up to 30 sectors is built, which in each sector has its time-dependent price setting to examine the consequences of this heterogeneity (Bils and Klenow 2004). Klenow and Kryvtsov (2008) and Nakamura and Steinsson (2008) also examines the same U.S.

CPI dataset for different area and time periods. Meanwhile, Altissimo, Ehrmann et al. (2006) and Dhyne, Álvarez et al. (2005) have published the results of their research on the data from the Euro area. One common important finding of these works is that there is substantial cross-sector heterogeneity in the frequency of price changes.

The question is how to incorporate this micro data evidence into a macro model. Dixon and Kara (2006) found an improved way to measure nominal rigidity than the ad hoc and unrealistic scheme of adding indexation to the Calvo model, which they called the Generalised Taylor Economy (GTE). The GTE model better characterises the economy and incorporates the distribution of contract lengths using empirical micro data. In the GTE there are many sectors in the economy, each sector features a simple Taylor type wage contract and the fixed wage duration in each sector differs in the aggregate economy. They found that GTE wage setting behaviour can generate greater persistence of output deviations than the conventional simple Taylor type contract in the closed economy, with the same calibration value as Chari, Kehoe and Mcgrattan (2000) and Ascari (2000) who are pessimistic for staggered Taylor contracts. The reason behind this is the 'spill-over effect' in which the presence of a longer contract can hold back the general price level in response of monetary shocks, which in turn influences the shorter contracts to adjust less than they are able to.

Besides to model the heterogeneous stickiness across different sectors, Wolman (1999) and Dixon and Le Bihan (2010) developed a Generalised Calvo (GC) price-staggering model where the price reset probabilities differ over the time span. In this setup, the conventional Calvo contract which cannot fit the criterion that all of the firms' prices will end at a maximum number of periods is modified and the long tail in the price dispersion is no longer a problem to affects the model's implication.

Carvalho (2006) has also constructed another heterogeneous stickiness model which is the Multiple Calvo (MC) price setting model. In this model there are several sectors in the economy and each sector has its sector specific reset probability. This shows that the real effect of monetary policy is more persistent than in the conventional Calvo price setups. Carvalho (2006) finds that there are two reasons why heterogeneous price durations can increase persistence of the real variables: the first is the timing effect whereby the longer price contracts dominates the output dynamics as time goes by, the second reason is the spill-over effect whereby the longer price contracts can hold back the aggregate price level.

Further work done by Jiang (2009) who compares different heterogeneous price stickiness (i.e. GTE, MC and GC) using U.S. micro price data and quantitatively finds that those pricing models consistent with distribution of price durations from the micro evidence can improve persistence substantially relative to the conventional Calvo and Taylor setup, both in the short run and long run. She shows that all three approaches to model heterogeneous stickiness (GC, GTE and MC) lead to the similar responses to a productivity shock because they share the same steady state distribution of price durations. Dixon and Kara (2010) evaluate different types of price setting by allowing a distribution of durations from micro data evidence. They suggest that GTE is the only model that can satisfy inflation persistence in both the macro and micro data evidence. Dixon and Le Bihan(2010) incorporate the GTE and GC price and wage settings into SW(2003) framework and find that these alternative models can also replicate inflation and output persistence following shocks. In addition, they find that the GTE is the only model which can generate the hump-shaped response of inflation and output persistence to monetary policy shocks.

2.3 The Model Economy

The model that is used in this thesis is based on SW (2003) which has been extended for one distinctive departure, which is the price staggering structure. Together with CEE (2005), SW (2003) applies a simple Calvo price setting with partial indexation and examines its consequences to mimic the main characteristics of empirical data, whereas in this section heterogeneous price stickiness (GTE and GC model) are considered in this framework. Although the micro price data has been studies widely for a range of countries, relevant wage data are harder to find. Thus, the wage setting in this thesis is still in line with SW (2003) which is set as Calvo with partial indexation scheme. The way to model heterogeneous wage stickiness is not included in the scoop of this thesis due to the shortage of micro wage data evidence. [4]

The model is the application of a RBC methodology to an economy with sticky prices and wages. There are four sectors in the economy, namely: households, intermediate goods firms, final goods firms, and government. Households' maximise a utility function with two arguments (i.e. goods and labour) over an infinite life horizon. Consumption which appears in the utility function is related to a time-varying external habit variable. Labour is differentiated over households, so that the households can react as wage setters to exert some monopoly power over their type of labour, which results in an explicit wage equation and allows for the introduction of sticky nominal wages following Calvo with Indexation setting. Households allocate wealth among cash on the one hand and riskless bonds on the other hand. Households also rent capital services to firms and decide how much capital to accumulate given certain

[4] Theoretical heterogeneous wage setting equations are presented in Appendix 1.

capital adjustment costs. As the rental rate of capital goes up, the capital stock can be used more intensively according to some cost schedule.

On the side of production, there is continuum of intermediate goods firms in a monopolistic competition and the final goods market is a perfectly competitive market. Firms seek to maximise profits by hiring labour and buying capital in order to produce differentiated goods. The monopolistic power of intermediate firms makes them act as a price setter who can set price in accordance with different price strategies. Labour is differentiated over households, given this, there is some monopoly power over wages that the firms choose any level of labour at ongoing wage rate so that the costs of hiring any extra workers are compensated by the extra revenues that they generate. Turning to the Government sector, it applies an empirical monetary policy reaction function to influence the economy which is assumed to describe how nominal interest rate is set by monetary authority.

In time dependent models, the price and wage settings have restrictive implications for the distributions of durations. The simple Taylor model setting is that all durations of contract are identical. The simple Calvo model setting assumes that the reset probability of price and wage setting is constant over time. The standard time-dependent model cannot replicate the real world economy, in which there exist many different sectors in the economy. In this thesis the heterogeneity concept is introduced into the price setting models, which is defined as GTE and GC set-ups that allow the distribution of durations implied by the pricing model to be exactly the same as the distribution found in the actual micro-data evidence.

2.3.1 Final Goods Firms

At time *t*, a final consumption goods, Y_t, is produced by a final goods firm in a perfectly competitive market. The final goods firm does this by combining a continuum of intermediate goods, indexed by $f \in (0,1)$, using a constant return to scale technology of the Dixit and Stiglitz (1977) form, as in the following equation:

$$Y_t = \left[\int_0^1 Y_{ft}^{\frac{1}{1+\lambda_{p,t}}} df \right]^{1+\lambda_{p,t}} \tag{2.1}$$

Where Y_t is the final goods and Y_{ft} denotes the time *t* input of intermediate goods *f*; $\lambda_{p,t}$ is a stochastic parameter that determines the time-varying mark-up in the goods market; $1+\lambda_{p,t}$ is the markup of prices over marginal cost at the intermediate goods level; assuming that $\lambda_{p,t} = \lambda_p + \eta_t^p$, where η_t^p is an i.i.d-Normal. Shocks to this parameter η_t^p will be interpreted as a 'cost-push' shock.

Let P_t and P_{ft} denote the price of the final goods and intermediate goods *f* in time *t*, respectively. Final goods firms' maximise profit as in the following equation:

$$\max_{Y_t, Y_{ft}} \prod = Y_t P_t - \int_0^1 Y_{ft} P_{ft} \, df$$

subject to

$$Y_t = \left[\int_0^1 Y_{ft}^{\frac{1}{1+\lambda_{p,t}}} df \right]^{1+\lambda_{p,t}}$$

The optimally conditions yield,

$$\partial Y_t : P_t - \lambda_t \cdot \frac{1}{1+\lambda_{p,t}} \cdot Y_t^{-\frac{\lambda_{p,t}}{1+\lambda_{p,t}}} = 0$$

$$\partial Y_{ft} : P_{ft} - \lambda_t \cdot \frac{1}{1+\lambda_{p,t}} \cdot Y_{ft}^{-\frac{\lambda_{p,t}}{1+\lambda_{p,t}}} = 0$$

which implies that the demand of the intermediate goods, or equivalently total household demand for intermediate goods, is given by:

$$Y_{ft} = \left(\frac{P_{ft}}{P_t} \right)^{-\frac{1+\lambda_{p,t}}{\lambda_{p,t}}} Y_t \tag{2.2}$$

According to equation above, the demand for intermediate good *f* is a decreasing function of the relative price of that good and an increasing function of the aggregate output Y_t. The elasticity of substitution between goods is $1+\lambda_{p,t}/\lambda_{p,t}$. Integrating this equation and imposing the final goods production function, the following relationship between the price of the final good and the price of the intermediate goods can be derived:

$$P_t = \left[\int_0^1 P_{ft}^{-\frac{1}{\lambda_{p,t}}} df \right]^{-\lambda_{p,t}} \tag{2.3}$$

2.3.2 Intermediate Goods Firms

There is a continuum of monopolistically competitive firms indexed by *f* on the unit interval. They produce differentiated goods. Intermediate goods $f \in (0,1)$ are produced by a monopolist who hires capital and labour at the rental rate of capital r_t^k and wage rate W_t , respectively. Every intermediate firm faces the same Cobb-Douglas production function, with an identical level of total factor productivity z_t, which uses the following technology:

$$Y_{ft} = \varepsilon_t^a \tilde{K}_{ft}^{\alpha} L_{ft}^{1-\alpha} - \phi \tag{2.4}$$

where $0 < \alpha < 1$ states the division of capital and labour in the production function and ε_t^a is the total factor productivity shock which follows the AR(1) process $\varepsilon_t^a = \rho_a \varepsilon_{t-1}^a + \eta_t^a, \eta_t^a \sim N(0, \sigma_a)$. In addition, $\phi > 0$ denotes the fixed cost of production. Here, L_{ft} and $\tilde{K}_{ft}$ denote the time *t* aggregate labour input and effective utilisation of the capital services used to produce the f^{th} intermediate goods, which is given by $K_{ft} = z_t K_{f,t-1}$.

The intermediate firm chooses an optimal bundle of capital stock and labour services in order to minimise its costs. Cost minimisation is given by:

$$\min_{L_{ft}, \tilde{K}_{ft}} TC = W_t L_{ft} + R_t^k \tilde{K}_{ft}$$

where W_t is the aggregate nominal wage rate and R_t^k is the nominal rental rate on capital subject to the supply of goods:

$$Y_{ft} = \varepsilon_t^a \tilde{K}_{ft}^{\alpha} L_{ft}^{1-\alpha} - \phi$$

where the FOCs are:

$$\partial L_{ft} : W_t - \lambda_t \cdot (1-\alpha) \cdot \varepsilon_t^a \cdot \tilde{K}_{ft}^{\alpha} \cdot L_{ft}^{-\alpha} = 0$$
$$\partial \tilde{K}_{ft} : R_t^k - \lambda_t \cdot \alpha \cdot \varepsilon_t^a \cdot \tilde{K}_{ft}^{\alpha-1} \cdot L_{ft}^{1-\alpha} = 0$$

which implies that:

$$\frac{W_t L_{ft}}{R_t^k \tilde{K}_{ft}} = \frac{1-\alpha}{\alpha} \qquad (2.5)$$

Given constant return to scale, the capital-labour ratio will be identical across intermediate goods producers and it will be equal to the aggregate capital-labour ratio.

Intermediate firms rent capital and labour in perfectly competitive factor markets. Profits are distributed to households at the end of each time period. The firm's marginal cost is given by:

$$MC = \frac{dTC}{dY} = \mathrm{W} \cdot \frac{dL}{dY} + R_t^k \cdot \frac{dK}{dY}$$
$$TC = W \cdot L + R_t^k \cdot K$$
$$L = \left(\frac{Y}{\varepsilon_t^a K^{\alpha}} \right)^{\frac{1}{1-\alpha}}$$
$$K = \left(\frac{Y}{\varepsilon_t^a L^{1-\alpha}} \right)^{\frac{1}{\alpha}}$$

Then the nominal marginal cost MC_t for producing one extra unit of intermediate goods input is the same for all firms and is equal to:

$$MC_t = \frac{1}{\varepsilon_t^a} W_t^{1-\alpha} \left(R_t^k\right)^{\alpha} \left[\alpha^{-\alpha}\left(1-\alpha^{-(1-\alpha)}\right)\right] \tag{2.6}$$

This implies that the marginal cost is independent of the intermediate goods produced.

In flexible economy, the intermediate good firm's time t profits are:

$$\max \prod = P_{ft} Y_{ft} - TC \cdot Y_{ft}$$

subject to:

$$Y_{ft} = \left(\frac{P_{ft}}{P_t}\right)^{-\frac{1+\lambda_{p,t}}{\lambda_{p,t}}} Y_t$$

Profit maximisation implies:

$$MR = MC$$

Since:

$$MR = \frac{dTR}{dY} = \frac{dP_{ft}}{dY_{ft}} \cdot Y_{ft} + \frac{dY_{ft}}{dY_{ft}} \cdot P_{ft} = P_{ft}\left(1 - \frac{\lambda_{p,t}}{1+\lambda_{p,t}}\right)$$

Then:

$$P_{ft}^{*} = \left(1+\lambda_{p,t}\right) \cdot \frac{1}{\varepsilon_t^a} W_t^{1-\alpha} \left(R_t^k\right)^{\alpha} \left[\alpha^{-\alpha}\left(1-\alpha^{-(1-\alpha)}\right)\right] \tag{2.7}$$

The optimal flexible price is a markup over marginal cost.

2.3.2.1 The Generalised Taylor Economy Price Setting Model

In the Generalised Taylor Economy (GTE), which has been developed by Dixon and Kara(2005) and Dixon (2010), the economy is subset into *N* sectors, $i=1,\ldots,N$. In sector *i* there is a *i*-period conventional Taylor price staggering process with *i* equally-size cohorts of firms, cohorts in sector *i* is denoted by *j* with equal size $j=1,\ldots,i$, which means that the number of cohorts are equal to the number of periods and that the prices are fixed and the contract length is the same for all cohorts within a sector. Cohorts only differ in the timing of their price-setting, whereas sectors solely differ in the length of contract. So in each period a share of i^{-1} cohorts in sector *i* set a new price (or wages). Assuming that the economy is a continuum of firms, the GTE can be described as a vector of sector shares: α_i is the proportion of firms that have price-spells of length *i*. If the longest observed price-spell is *N*, then $\sum_{i=1}^{N}\alpha_i = 1$ and $\alpha = (\alpha_1, \cdots, \alpha_N)$ is the *N*-sector of shares. The 'sectors' can be defined by the length of price-spells. The essence of the Taylor model is that when they set the price, the firm knows exactly how long its price is going to last. The simple Taylor economy is a special case where is only one length of price-spell in the economy. The GTE is based on the cross-sectional distribution of completed spell lengths, which can also be called the distribution across firms of completed contract (DAF) in this context. The GTE has been developed in Taylor (1993), Dixon and Kara (2005, 2006, 2010), Coenen, Levin et al. (2007), and Kara (2010). The GTE can represent any steady-state distribution of durations; hence, it can be chosen to exactly reflect the distribution found in the micro-data.

The intermediate firms of cohort j in sector i maximise their profit by choosing the optimal reset-price $\tilde{P}_{i,t}^{GTE}$:

$$\max_{\tilde{P}_{ij,t},Y_{ij,t}} \sum_{t=1}^{t+i-1} \beta^{t-1} \left[\tilde{P}_{ij,t} - mc_t P_t \right] Y_{ij,t} - mc_t P_t \phi$$

subject to the demand function:

$$Y_{ij,t} = \left(\frac{P_{ij,t}}{P_t} \right)^{-\frac{1+\lambda_{p,t}}{\lambda_{p,t}}} Y_t$$

as well as the constraint that prices are fixed for i periods.

where mc_τ is the real marginal cost of production.

Solving the intermediate goods firm problem yields the optimal reset prices:

$$\tilde{P}_{i,t}^{GTE} = \frac{(\lambda_{p,t}+1)\sum_{t=1}^{t+i-1} \beta^{t-1} mc_t P_t^{\frac{2\lambda_{p,t}+1}{\lambda_{p,t}}} Y_t}{\sum_{t=1}^{t+i-1} \beta^{t-1} P_t^{\frac{\lambda_{p,t}+1}{\lambda_{p,t}}} Y_t} \tag{2.8}$$

Since all cohorts j within the sector i choose the same reset price, so subscript j can be suppressed in this reset price equation.

In each sector i, a proportion i^{-1} of the α_i firms reset their price at each date. Assuming imperfect competition and a standard demand curve, the optimal reset price in sector i $\tilde{P}_{i,t}^{GTE}$ is given by the first-order condition of an intertemporal profit-maximisation programme under the constraint implied by price rigidity.

The sectoral price is simply the average over i cohorts in the sector:

$$P_{i,t}^{GTE} = \frac{1}{i}\sum_{j=1}^{i}\tilde{P}_{i,t-j+1}^{GTE} \tag{2.9}$$

The aggregate price P_t is a weighted average of the sectoral prices P_{it}, where the weights of sectors in the economy are α_i :

$$P_t^{GTE} = \sum_{i=1}^{N}\alpha_i P_{i,t}^{GTE} \tag{2.10}$$

$$P_t^{GTE} = \left(\sum_{i=1}^{N}\sum_{j=1}^{i}\frac{\alpha_i}{i}\tilde{P}_{i,t+j-1}^{GTE}{}^{-\frac{1}{\lambda_{p,t}}}\right)^{-\lambda_{p,t}} \tag{2.11}$$

2.3.2.2 Simple Taylor Price Setting Model

In simple Taylor price settings, the duration of the price contract is fixed and firms know it ex ante. By applying the French micro price evidence (Dixon and Le Bihan 2010), the equivalent simple Taylor price setting are fixed at approximately four quarters, which can be considered as a special case of GTE where there is only one sector that exists in the economy.

The intermediate firms maximise their profit by choosing the optimal reset-price $\tilde{P}_t^{ST}$:

$$\max_{\tilde{P}_{f,t},Y_t} \sum_{t=1}^{t+i-1} \beta^{t-1} \left[\tilde{P}_{f,t} - mc_t P_t \right] Y_{f,t} - mc_t P_t \phi$$

subject to the demand function:

$$Y_{f,t} = \left(\frac{P_{f,t}}{P_t} \right)^{-\frac{1+\lambda_{p,t}}{\lambda_{p,t}}} Y_t$$

as well as the constraint that prices are fixed for *i* periods.

Thus, the optimal cohort reset price is:

$$\tilde{P}_t^{ST} = \frac{(\lambda_{p,t}+1)\sum_{t=1}^{4} \beta^{t-1} mc_t P_t^{\frac{2\lambda_{p,t}+1}{\lambda_{p,t}}} Y_t}{\sum_{t=1}^{4} \beta^{t-1} P_t^{\frac{\lambda_{p,t}+1}{\lambda_{p,t}}} Y_t} \tag{2.12}$$

The aggregate price is given by:

$$P_t^{ST} = \frac{1}{i} \sum_{i=1}^{4} \tilde{P}_{t-i}^{ST} \tag{2.13}$$

2.3.2.3 The Generalised Calvo Price Setting Model

The reset probability varies with the duration of the price in the Generalised Calvo Price Setting Model (GC), which is demonstrated by Wolman (1999), Mash(2002), Dixon (2006) and Sheedy (2004). The longer the price duration is, the higher the price reset probability will be. Both GC and GTE share the same steady-state distribution of price stickiness (Dixon 2010).

Suppose the longest length of price-spell is *N*, then $\omega_N = 1$ and $\omega_0 = 0$, then the profile of reset probabilities is:

$$\omega = \{\omega_i\}_{i=1}^{N}$$

In economic terms, the difference between the Calvo approach and the Taylor approach is that when the firm sets its price in Calvo type contract it does not know how long its price is going to last. Rather, it has a survivor function S(i), which gives the probability that its price will last up to *i* periods.

The survival rates are defined as:

$$\Omega_i = \prod\nolimits_{t=1}^{i}(1-\omega_{t-1}) \tag{2.14}$$

The standard Calvo model is a special case where the hazard rate is constant. In any actual data set, *N* is finite.

The reset price is common across all firms who reset their price. Let $\tilde{P}_t^{GC}$ denote the value of P_{ft} set by firm that can re-optimise at time *t* and $\tilde{P}_t^{GC}$ is not dependent on *f*.

The intermediate firm's profits are:

$$\max_{\tilde{P}_{ft}, Y_{ft}} \Pi = \sum_{i=1}^{N} \beta^i \Omega_i \left[\tilde{P}_{ft} - mc_{t+i-1} P_{t+i-1} \right] Y_{f,t+i-1} - mc_{t+i-1} P_{t+i-1} \phi$$

subject to:

$$Y_{ft} = \left(\frac{P_{ft}}{P_t} \right)^{-\frac{1+\lambda_{p,t}}{\lambda_{p,t}}} Y_t$$

which is then combined with the marginal cost equation:

$$MC_t = \frac{1}{\varepsilon_t^a} W_t^{1-\alpha} \left(R_t^k \right)^{\alpha} \left[\alpha^{-\alpha} \left(1 - \alpha^{-(1-\alpha)} \right) \right]$$

The first order condition associated with the firm's choice to get the optimal reset price $\tilde{P}_t^{GC}$ is:

$$\tilde{P}_t^{GC} = \frac{1}{\sum_{i=1}^{N} \Omega_i \beta^{i-1}} \sum_{i=1}^{N} \Omega_i \beta^{i-1} P_{t+i-1}^{*} \qquad (2.15)$$

The aggregate price level can be written as

$$P_t^{GC} = \sum_{i=1}^{N} \alpha_i^A \tilde{P}_{t-i+1}^{GC} = \bar{\omega} \sum_{i=1}^{N} \Omega_i \tilde{P}_{t-i+1}^{GC} \qquad (2.16)$$

where $\bar{\omega} = \sum_{i=1}^{N} \Omega_i^{-1}$ and $\Omega_i = \prod_{t=1}^{i} (1 - \omega_{t-1})$

That is, the current price level is constituted by the surviving reset prices of the present and last *N* periods.

2.3.2.4 Calvo with Indexation Price Setting Model

Under Calvo with Indexation Price Setting Model, the price setting follows Calvo setting in which firms are not allowed to change their prices unless they receive a random 'price-change signal'. The probability that a given price can be re-optimised in any particular period is constant and equal to $1-\xi_p$. In addition, those firms who cannot reset their price will be indexed with their price to past inflation.

The intermediate firms maximise profits:

$$\max_{\tilde{P}_{ft},Y_{ft}} \Pi = \sum_{i=1}^{N} \beta^i \left(1-\xi_p\right)^i \left\{\left[\tilde{P}_{f,t+i-1} - mc_{t+i-1}P_{t+i-1}\right]Y_{f,t+i-1} - mc_{t+i-1}P_{t+i-1}\phi\right\}$$

$$+\xi_p{}^i \left\{\left[\tilde{P}_{f,(t+i-1)-1}\left(\frac{P_{t+i-1}}{P_{t+i}}\right)^{\gamma_p} - mc_{t+i-1}P_{t+i-1}\right]Y_{f,t+i-1} - mc_{t+i-1}P_{t+i-1}\phi\right\}$$

subject to:

$$Y_{ft} = \left(\frac{P_{ft}}{P_t}\right)^{-\frac{1+\lambda_{p,t}}{\lambda_{p,t}}} Y_t$$

The first-order conditions derived from profit maximisation is given as follows:

$$E_t \sum_{i=0}^{\infty} \beta^i \xi_p^i \lambda_{p,t+i} Y_{f,t+i} \left(\frac{\tilde{P}_{ft}}{P_t}\left(\frac{\left(P_{t-1+i}/P_{t-1}\right)^{\gamma_p}}{P_{t+i}/P_t}\right) - \left(1+\lambda_{p,t+i}\right)mc_{t+i}\right) = 0$$

The aggregate price index is given by:

$$\left(P_t\right)^{-\frac{1}{\lambda_{p,t}}} = \xi_p \left(P_{t-1}\left(\frac{P_{t-1}}{P_{t-2}}\right)^{\gamma_p}\right)^{-\frac{1}{\lambda_{p,t}}} + \left(1-\xi_p\right)\left(\tilde{P}_{ft}\right)^{-\frac{1}{\lambda_{p,t}}} \qquad (2.17)$$

2.3.2.5 Simple Calvo Price Setting Model

In Simple Calvo price setting model, it is assumed that there is a proportion $1-\xi_p$ of firms can reset their prices, the rest proportion ξ_p of firms whose prices will survive as the same as last period. The survival rate is a constant randomly determined number.

The intermediate firms maximise profits:

$$\max_{\tilde{P}_{ft},Y_{ft}} \Pi = \sum_{i=1}^{N} \beta^i \left(1-\xi_p\right)^i \left\{\left[\tilde{P}_{f,t+i-1} - mc_{t+i-1}P_{t+i-1}\right]Y_{f,t+i-1} - mc_{t+i-1}P_{t+i-1}\phi\right\}$$
$$+\xi_p{}^i \left\{\left[\tilde{P}_{f,(t+i-1)-1} - mc_{t+i-1}P_{t+i-1}\right]Y_{f,t+i-1} - mc_{t+i-1}P_{t+i-1}\phi\right\}$$

subject to:

$$Y_{ft} = \left(\frac{P_{ft}}{P_t}\right)^{-\frac{1+\lambda_{p,t}}{\lambda_{p,t}}} Y_t$$

The first-order conditions derived from profit maximisation is given as follows:

$$E_t \sum_{i=0}^{\infty} \beta^i \xi_p^i \lambda_{p,t+i} Y_{f,t+i} \left(\frac{\tilde{P}_{ft}}{P_t} - \left(1+\lambda_{p,t+i}\right) mc_{t+i}\right) = 0$$

The aggregate price index is given by:

$$\left(P_t\right)^{-\frac{1}{\lambda_{p,t}}} = \xi_p \left(P_{t-1}\right)^{-\frac{1}{\lambda_{p,t}}} + \left(1-\xi_p\right)\left(\tilde{P}_{ft}\right)^{-\frac{1}{\lambda_{p,t}}} \tag{2.18}$$

2.3.3 Households

There is a continuum of monopolistically competitively households, indexed by $\tau \in (0,1)$, who supply differentiated labour services to the intermediated goods firms. Firms regard each household's labour services L_t^τ as an imperfect substitute for the labour services of other households, thus the labour market has a form of monopolistic competition. Again, a competitive bundler is assumed, who assembles all households' labour supplies L_t^τ at the wage rate W_t in the same proportions as firms would choose. Thus, the bundler's demand for each household's labour is equal to the sum of the firms' demands. The τ^{th} household makes a sequence of decisions of bonds and consumption purchase during each period.

The intertemporal utility function of the τ^{th} household over an infinite time horizon is given by:

$$E_0 \sum_{i=0}^{\infty} \beta^t E_t U_t^\tau \tag{2.19}$$

where β is the discount factor and E_t denotes the rational expectation operator in period t at the current state, and the instantaneous utility function is separable in consumption and labour:

$$U_t^\tau = \varepsilon_t^B \left\{ \frac{1}{1-\sigma_c} \left(C_t^\tau - H_t \right)^{1-\sigma_c} - \frac{\varepsilon_t^L}{1+\sigma_l} \left(L_t^\tau \right)^{1+\sigma_l} \right\} \tag{2.20}$$

where C_t^τ denotes the consumption of household τ . $H_t = hC_{t-1}$ assumed to be an external proportional to aggregate past consumption where h is a parameter describing habit formation; L_t^τ is hours worked by household τ ; σ_c measures the relative risk aversion; and σ_l is the inverse of elasticity of hours worked to the real wage rate. There are two shocks in the utility function: ε_t^B represents a general shock to preferences that affects the intertemporal substitution of households (preference shocks) while ε_t^L represents a shock to the labour supply. Both of the shocks are assumed to follow a first-order autoregressive process with independently identically distributed normal error, that is:

$$\varepsilon_t^B = \rho_B \varepsilon_{t-1}^B + \eta_t^B, \eta_t^B \sim N(0, \sigma_B)$$

$$\varepsilon_t^L = \rho_L \varepsilon_{t-1}^L + \eta_t^L, \eta_t^L \sim N(0, \sigma_L)$$

The household's intertemporal budget constraint is given by:

$$b_t \cdot \frac{B_t^\tau}{P_t} + C_t^\tau + I_t^\tau = \frac{B_{t-1}^\tau}{P_t} + Y_t^\tau \qquad (2.21)$$

Households hold their financial wealth in the form bonds B_t at the market price b_t. Current income and financial wealth resulting from bonds bought in the previous periods can be used for consumption and investment in physical capital or bonds.

The household's total income is given by:

$$Y_t^\tau = \left(W_t^\tau L_t^\tau + A_t^\tau\right) + \left(R_t^k z_t^\tau K_{t-1}^\tau - \psi\left(z_t^\tau\right) K_{t-1}^\tau\right) + Div_t^\tau - T_t^\tau \qquad (2.22)$$

Total income consists mainly of four components: the first is labour income $W_t^\tau L_t^\tau$ plus state-contingent securities security payoffs A_t^τ; the second component is the return on real capital stock $R_t^k z_t^\tau K_{t-1}^\tau$, depending of the rate of capital utilization z_t minus the cost associated with various in the degree of capital utilization $\psi(z_t^\tau)K_{t-1}^\tau$;

the third component are the dividends which are derived from the imperfectly competitive intermediate firms Div_t^τ; and the last component is the lump-sum tax T_t^τ.

Following CEE(2005), there exist state-contingent securities that insure the household's income will be equal to aggregate labour income and as a consequence, the marginal utility of wealth, individual consumption, level of capital holdings, bond holdings and dividends will be identical across different types of households.

2.3.3.1 Consumption, Investment, and Capital Accumulation

Households own the capital stock and they rent out to the intermediate goods firm-producers at a given rental rate of R_t^k. They can increase the supply of rental services from capital either by investing in additional capital I_t, which takes one period to be installed, or by changing the utilisation rate of already installed capital z_t.

Households choose the capital stock, investment and the utilisation rate in order to maximise their intertemporal objective function subject to the intertemporal budge constraint and also the capital accumulation equation, which is given by:

$$K_t = K_{t-1}\left[1-\delta\right]+\left[1-S\left(\varepsilon_t^I \cdot I_t \big/ I_{t-1}\right)\right]\cdot I_t \qquad (2.23)$$

where I_t is gross investment, δ is the depreciation rate, and the investment adjustment cost function $S(\cdot)$ is a positive function of changes in investment, with

$S(1)=0, S'(1)=0, S''(1)>0$. Assuming that shocks to the investment cost function follow a first-order autoregressive process with an i.i.d-normal: $\varepsilon_t^I = \rho_I \varepsilon_{t-1}^I + \eta_t^I$.

Households maximise a separable utility function with two arguments (i.e. goods and labour efforts) over an infinite life horizon subject to the intertemporal budget constraint and capital accumulation equation. In equilibrium households will make the same choices for consumption, hours worked, bonds, investment and capital utilisation.

$$L = E_t \sum_{t=0}^{\infty} \beta^t \left\{ \varepsilon_t^B \left[\frac{1}{1-\sigma_c} \left(C_t^\tau - H_t \right)^{1-\sigma_c} - \frac{\varepsilon_t^L}{1+\sigma_l} \left(L_t^\tau \right)^{1+\sigma_l} \right] \right\}$$
$$-\lambda_t \beta^t \left[C_t^\tau + I_t^\tau - W_t^\tau L_t^\tau - A_t^\tau - Div_t^\tau - \left(R_t^k z_t^\tau K_{t-1}^\tau - \psi(z_t^\tau) K_{t-1}^\tau \right) - \frac{B_{t-1}}{P_t} + b_t \frac{B_t}{P_t} \right]$$
$$-\mu_t \beta^t \left[K_t - (1-\delta) K_{t-1} - I_t \left(1 - S\left(\frac{\varepsilon_t^I I_t}{I_{t-1}} \right) \right) \right]$$

The first-order conditions with respect to consumption, hours worked, bond holdings, capital stock, investment and capital utilisation rate can be written as:

$$\partial C_t^\tau : \lambda_t = U_{c,t} = \varepsilon_t^B \cdot \left(C_t^\tau - H_t \right)^{-\sigma_c} \tag{2.24}$$

$$\partial L_t^\tau : \lambda_t \cdot W_t^\tau = U_{l,t} = \varepsilon_t^B \cdot \varepsilon_t^L \cdot \left(L_t^\tau \right)^{\sigma_l} \tag{2.25}$$

$$\partial \frac{B_t^\tau}{P_t} : E_t \left[\beta \cdot \frac{\lambda_{t+1}}{\lambda_t} \cdot \frac{R_t P_t}{P_{t+1}} \right] = 1 \tag{2.26}$$

$$\partial K_t \Rightarrow Q_t = E_t \left[\beta \frac{\lambda_{t+1}}{\lambda_t} \left(Q_{t+1}(1-\delta) + z_{t+1}^\tau R_{t+1}^k - \psi(z_{t+1}^\tau) \right) \right] \tag{2.27}$$

$$\partial I_t \Rightarrow Q_t S'\left(\frac{\varepsilon_t^I I_t}{I_{t-1}} \right) \frac{\varepsilon_t^I I_t}{I_{t-1}} - E_t \left[\beta Q_{t+1} \cdot \frac{\lambda_{t+1}}{\lambda_t} S'\left(\frac{\varepsilon_{t+1}^I I_{t+1}}{I_t} \right) \left(\frac{\varepsilon_{t+1}^I I_{t+1}}{I_t} \right) \frac{I_{t+1}}{I_t} \right] + 1 = Q_t \left(1 - S\left(\frac{\varepsilon_t^I I_t}{I_{t-1}} \right) \right) \tag{2.28}$$

$$\partial z_t^{\tau} \Rightarrow R_t^k = \psi'\left(z_t^{\tau}\right) \tag{2.29}$$

where R_t is the gross nominal rate of return on bonds ($R_t = 1 + i_t = 1/b_t$)and λ_t is the marginal utility of consumption. Q_t defines the real value of installed capital, also name as Tobin's Q. The value of installed capital Q_t depends on the expected future value taking into account the appreciation rate and the expected future return as captured by the rental rate times the expected rate of capital utilisation.

The cost of capital utilisation is equal to the rental rate of capital services. As the rental rate increases it becomes more profitable to use the capital stock and also more intensively up to the point where the extra gains match the extra output costs. The variable capital utilisation is used to reduce the impact of changes in output on the rental rate of capital and, therefore, it smoothes the response of marginal cost to fluctuations in output.

2.3.3.2 Labour Supply and Wage Setting Behaviour

Households supply their homogenous labour to an intermediate labour union that differentiates the labour services and acts as price-setters in the labour market. It supplies labour to a representative, competitive firm that transforms it into an aggregate labour input, L_t, following Dixit-Stiglitz-type aggregator functions:

$$L_t = \left[\int_0^1 \left(L_t^{\tau} \right)^{\frac{1}{1+\lambda_{w,t}}} d\tau \right]^{1+\lambda_{w,t}} \tag{2.30}$$

where $\lambda_{w,t} = \lambda_w + \eta_t^w$, where $1+\lambda_t^v$ will be the markup of real wages over the ratio of marginal disutility of labour to the marginal utility of consumption in a flexible economy. η_t^w is an i.i.d.-normal, which is a wage markup shock.

Firm minimise the cost problem to choose an optimal amount of labour service:

$$\min_{L_t, L_t^\tau} W_t L_t - \int_0^1 W_t^\tau L_t^\tau \, d\tau$$

subject to:

$$L_t = \left[\int_0^1 \left(L_t^\tau \right)^{\frac{1}{1+\lambda_{w,t}}} d\tau \right]^{1+\lambda_{w,t}}$$

Then, the demand for labour which is determined by:

$$L_t^\tau = \left(\frac{W_t^\tau}{W_t} \right)^{-\frac{1+\lambda_{w,t}}{\lambda_{w,t}}} L_t \qquad (2.31)$$

where W_t is the aggregate wage rate, and the price of L_t, which is related to individual households wages W_t^τ, via the relationship:

$$W_t = \left[\int_0^1 \left(W_t^\tau \right)^{-\frac{1}{\lambda_{w,t}}} d\tau \right]^{-\lambda_{w,t}} \qquad (2.32)$$

Wages can only be optimally reset after some random 'wage-change signal' is received. The probability that households can change their nominal wage in period *t* is constant and equal to $1-\xi_w$, and γ_w is the degree of wage indexation, which means that when households cannot optimise their wages, the current wages are adjusted by past inflation. When $\gamma_w = 0$ there is no indexation, and when $\gamma_w = 1$ there is perfect indexation to past inflation.

The re-optimised wage is derived from the household maximisation problem:

$$\frac{\tilde{W}_t}{P_t} \cdot E_t \sum_{i=0}^{\infty} \beta^i \xi_w^i \left(\frac{\left(P_t / P_{t-1}\right)^{\gamma_w}}{P_{t+i} / P_{t+i-1}} \right) \cdot \frac{L_{t+i}^h U_{c,t+i}}{1+\lambda_{w,t+i}} = E_t \sum_{i=0}^{\infty} \beta^i \xi_w^i L_{t+i}^h U_{l,t+i}$$

where $U_{l,t+i}$ is the marginal disutility of labour and $U_{c,t+i}$ is the marginal utility of consumption.

The aggregate wage index is given by:

$$\left(W_t\right)^{-\frac{1}{\lambda_{w,t}}} = \xi_w \left(W_{t-1} \left(\frac{P_{t-1}}{P_{t-2}} \right)^{\gamma_w} \right)^{-\frac{1}{\lambda_{w,t}}} + \left(1-\xi_w\right)\left(\tilde{W}_t\right)^{-\frac{1}{\lambda_{w,t}}} \tag{2.33}$$

2.3.4 Government Policies

The government spending rule is financed by lump sum taxation, which has no effect either on household's utility or on the firm's profit:

$$G_t = T_t$$

The central bank follows a nominal interest rate rule by adjusting its instrument in response to deviations of inflation and output from their respective target levels. In order to maintain the money market equilibrium, the money supply adjusts endogenously to meet the money demand at that interest rate. In capital market, equilibrium means that government debt is held by domestic investors at the market interest rate R_t :

$$\frac{R_t}{R^*} = \left(\frac{R_{t-1}}{R^*}\right)^{\rho_R} \left[\left(\frac{\pi_t}{\pi^*}\right)^{\psi_1} \left(\frac{Y_t}{Y^*}\right)^{\psi_2} \right]^{1-\rho_R} \left(\frac{Y_t / Y_{t-1}}{Y_t^* / Y_{t-1}^*}\right)^{\psi_3} \eta_t^R \tag{2.34}$$

where ρ_R determines the degree of interest rate smoothing and η_t^R is the monetary policy shock. The central bank supplies the money demanded by the household to support the desired nominal interest rate.

2.3.5 General Equilibrium

The final goods market is in equilibrium if production equals demand by households for consumption, investment, and the government expenditure:

$$Y_t = C_t + G_t + I_t + \psi(z_t) K_{t-1} \tag{2.35}$$

The capital rental market is in equilibrium when the demand for capital by the intermediate goods producers equals the supply by the households:

$$\int_0^1 \tilde{K}_{f,t-1} df = \tilde{K}_{t-1} \tag{2.36}$$

The labour market is in equilibrium if firm's demand for labour equals labour supply at the wage level set by households:

$$\left(\int_0^1 \left(L_{t-1}^{\tau}\right)^{\frac{1}{1+\lambda_{w,t}}} d\tau\right)^{1+\lambda_{w,t}} = L_t \tag{2.37}$$

The interest rate rule is determined by a reaction function that describes monetary policy decisions. To maintain money market equilibrium, the money supply adjusts endogenously to meet the money demand at those interest rates. Equilibrium in the capital market means that the government debt is held by domestic investors at the market interest rate R_t .

2.3.6 Summary of the Linearised Model

In order to solve the model it is log-linearised around a deterministic zero-inflation steady-state according to $X_t = \bar{X}e^{\hat{x}_t}$, and then $\hat{x}_t = \log(X_t / \bar{X})$. Hence the variables in logarithmic deviations from the steady state are denoted by the $\wedge$ hat symbol. The system of the linearised equations that fully characterise the equilibrium dynamics are described below.

The dynamic consumption equation with external habit formation is given by:

$$\hat{C}_t = \frac{h}{1+h}\hat{C}_{t-1} + \frac{1}{1+h}E_t\hat{C}_{t+1} - \frac{1-h}{(1+h)\sigma_c}\left(\hat{R}_t - E_t\hat{\pi}_{t+1}\right) + \frac{1-h}{(1+h)\sigma_c}\hat{\varepsilon}_t^B \qquad (2.38)$$

Consumption depends on a weighted average of past and expected future consumption, also the ex ante real interest rate and a disturbance term. Without habit formation, the consumption equation becomes strictly forward-looking. This real rigidity also influences the interest rate elasticity of consumption.

The investment equation is given by:

$$\hat{I}_t = \frac{1}{1+\beta}\hat{I}_{t-1} + \frac{\beta}{1+\beta}E_t\hat{I}_{t+1} + \frac{\varphi}{1+\beta}\hat{Q}_t + \hat{\varepsilon}_t^I \tag{2.39}$$

where $\varphi = 1/\overline{S}''$, which is the inverse of steady-state elasticity of the investment adjustment cost function. The investment depends on its weighted previous future value, also as well as the value of capital stock and disturbance term. A positive shock to the adjustments cost function $\hat{\varepsilon}_t^I$ temporarily reduces investment.

The corresponding Q equation is given by:

$$\hat{Q}_t = -\left(\hat{R}_t - E_t\hat{\pi}_{t+1}\right) + \frac{1-\delta}{1-\delta+\overline{r}_k}E_t\hat{Q}_{t+1} + \frac{\overline{r}_k}{1-\delta+\overline{r}_k}E_t\hat{R}_{t+1}^k + \hat{\eta}_t^Q \tag{2.40}$$

where $\beta = 1/(1-\delta+\overline{r}_k)$. The current value of capital stock depends negatively on the ex ante interest rate, and positively on its expected future value and the expected rental rate. Although η_t^Q is the only shock which does not arise from the structure of the economy, it reflects the alterations in the cost of capital caused by stochastic variations in the external finance premium.

The capital accumulation equation is standard:

$$\hat{K}_t = \left(1-\delta\right)\hat{K}_{t-1} + \delta\hat{I}_{t-1} \tag{2.41}$$

The optimal flexible price in log-linearised expression is given as:

$$\hat{P}_t^* = \alpha \cdot \hat{R}_t^k + (1-\alpha)\hat{W}_t - \hat{\varepsilon}_t^a + \hat{\eta}_t^p = M\hat{C}_t + \hat{\eta}_t^p \tag{2.42}$$

The inflation is defined as:

$$\hat{\pi}_t = \hat{P}_t - \hat{P}_{t-1} \qquad (2.43)$$

The log-linearised equation for the optimal reset price in GTE, which is an average over the optimal flex prices for the duration of the contract, is then given by:

$$\hat{\hat{P}}^{GTE}_{i,t} = \frac{\sum_{i=1}^{t+i-1} \beta^i E_t \hat{P}^*_t}{\sum_{i=1}^{t+i-1} \beta^i} \qquad (2.44)$$

where β is the discount factor, E_t is the expectation operator conditional on information available at date *t*, and $\hat{P}^*_t$ is the linearised optimal flex price at time *t+j-1*.

The aggregate price index in GTE price setting is:

$$\hat{P}^{GTE}_t = \sum_{i=1}^{N} \frac{\alpha_i}{i} \left(\sum_{j=1}^{i} \hat{\hat{P}}^{GTE}_{i,t+j-1} \right) \qquad (2.45)$$

The optimal cohort reset price in simple Taylor Price Setting is:

$$\hat{\hat{P}}^{ST}_t = \frac{\sum_{i=1}^{4} \beta^{i-1} E_t \hat{P}^*_{t+i}}{\sum_{i=1}^{4} \beta^{i-1}} \qquad (2.46)$$

The aggregate price in simple Taylor Price Setting is given as:

$$P^{ST}_t = \frac{1}{i} \sum_{i=1}^{4} \hat{\hat{P}}^{ST}_{t-i} \qquad (2.47)$$

The optimal reset price setting in GC model is given by:

$$\hat{\tilde{P}}_t^{GC} = \frac{1}{\sum_{i=1}^{N}\Omega_i \beta^{i-1}} \sum_{i=1}^{N} \Omega_i \beta^{i-1} \hat{P}_{t+i-1}^{*} \tag{2.48}$$

The aggregate price in GC model is given by:

$$\hat{P}_t^{GC} = \bar{\omega} \sum_{i=1}^{N} \Omega_i \hat{\tilde{P}}_{t-i+1}^{GC} \tag{2.49}$$

The Calvo with Indexation Price Setting rule is given by:

$$\hat{\pi}_t = \frac{\beta}{1+\beta\gamma_p} E_t \hat{\pi}_{t+1} + \frac{\gamma_p}{1+\beta\gamma_p} \hat{\pi}_{t-1} + \frac{1}{1+\beta\gamma_p} \frac{\left(1-\beta\xi_p\right)\left(1-\xi_p\right)}{\xi_p} \left[\alpha \hat{R}_t^k + (1-\alpha)\left(\hat{W}_t - \hat{P}_t\right) - \varepsilon_t^A\right] + \eta_t^p \tag{2.50}$$

The simple Calvo Price Setting rule is given by:

$$\hat{\pi}_t = \beta E_t \hat{\pi}_{t+1} + \frac{\left(1-\beta\xi_p\right)\left(1-\xi_p\right)}{\xi_p} \left[\alpha \hat{R}_t^k + (1-\alpha)\left(\hat{W}_t - \hat{P}_t\right) - \varepsilon_t^A\right] + \eta_t^p \tag{2.51}$$

The original wage equation in terms of Calvo with indexation setting is given as follows:

$$\hat{w}_t = \frac{\beta}{1+\beta} E_t \hat{w}_{t+1} + \frac{1}{1+\beta} \hat{w}_{t-1} + \frac{\beta}{1+\beta} E_t \hat{\pi}_{t+1} - \frac{1+\beta\gamma_w}{1+\beta} \hat{\pi}_t + \frac{\gamma_w}{1+\beta} \hat{\pi}_{t-1}$$
$$- \frac{1}{1+\beta} \frac{(1-\beta\xi_w)(1-\xi_w)}{(1+\frac{(1+\lambda_w)\sigma_L}{\lambda_w})\xi_w} [\hat{w}_t - \sigma_L \hat{L}_t - \frac{\sigma_c}{1-h}(\hat{C}_t - h\hat{C}_{t-1}) - \hat{\varepsilon}_t^L] + \hat{\eta}_t^w \tag{2.52}$$

The labour demand equation is given by:

$$\hat{L}_t = -\hat{W}_t + (1+\psi)\hat{R}_t^k + \hat{K}_{t-1} \tag{2.53}$$

where $\psi = \dfrac{\psi'(1)}{\psi''(1)}$ is the inverse of the elasticity of the capital utilisation cost function.

The good market equilibrium condition can be written as:

$$\hat{Y}_t = \left(1-\delta k_y - g_y\right)\hat{C}_t + \delta k_y \hat{I}_t + \hat{\varepsilon}_t^G = \phi \hat{\varepsilon}_t^a + \phi\alpha\hat{K}_{t-1} + \phi\alpha\psi\hat{R}_t^k + \phi\left(1-\alpha\right)\hat{L}_t \tag{2.54}$$

where k_y is the steady state capital-output ratio, g_y is the steady state government spending-output ratio, and ϕ is one plus the share of the fixed cost in production. Assuming that the exogenous spending follows a first-order autoregressive process with an i.i.d-normal error term and is also affected by the productivity shock as follows: $\varepsilon_t^G = \rho_G \varepsilon_{t-1}^G + \eta_t^G$. Output is produced using capital and labour services. Total factor productivity is assumed to follow a first-order autoregressive process: $\varepsilon_t^a = \rho_a \varepsilon_{t-1}^a + \eta_t^a$.

Finally, the model is closed by adding the following empirical monetary policy reaction function:

$$\hat{R}_t = \rho\hat{R}_{t-1} + (1-\rho)\left[\bar{\pi}_t + r_\pi(\hat{\pi}_{t-1} - \bar{\pi}_t) + r_y(\hat{Y}_t - \hat{Y}_t^p)\right] + r_{\Delta\pi}(\hat{\pi}_t - \hat{\pi}_{t-1}) + r_{\Delta y}[(\hat{Y}_t - \hat{Y}_t^p) - (\hat{Y}_{t-1} - \hat{Y}_{t-1}^p)] + \eta_t^R \tag{2.55}$$

The monetary authorities gradually respond to deviations of lagged inflation from an inflation objective. The parameter ρ captures the degree of interest rate smoothing. In addition, there is a feedback effect from the current change in inflation and the current growth rate in output. Finally, two monetary policy shocks are assumed, which are included in the Taylor Rule equation: the first is a persistent shock to the inflation objective $\overline{\pi}_t$, while the second is a temporary interest rate shock η_t^R, which also denoted as a monetary policy shock.

The equations above determine the endogenous variables of the model. These five models only differ in the price setting part, the rest of the model to describe the structure of the economy are common among all of the models. The stochastic behaviour of the system of linear rational expectations equation is driven by ten exogenous shock variables, which are: five shocks arising from technology and preferences, three 'cost-push' shocks, and two monetary policy shocks. The first set of shock variables is assumed to follow an independent first-order autoregressive stochastic process, whereas the second and third set is assumed to be i.i.d. processes.

2.4 Micro Data Evidence

The research on the empirical evidence of price stickiness has become more and more important in economic research around the world. Bils and Klenow (2004) were the first to investigate the average monthly frequencies of price changes in continuous time in 350 categories of consumption goods, which includes almost 70% of the US CPI from 1995 to 1997. In this thesis, the micro price evidence of the French economy which was collected by Le Bihan is used and the details of the calibration of the French micro data which are shown in Dixon and Le Bihan (2010). French data is used because it can be considered to be a good proxy for the whole Euro area since Dhyne, Álvarez et al. (2005) shows that there is a large degree of similarity across the larger Euro area economies. The micro-data sample in Dixon and Le Bihan (2010) lasts from July 1994 to February 2003, which contains around 13 million monthly price observations. This data covers 65% of the French CPI data. An individual observation is a price quote P_{jkt} for product *j* at outlet *k* at time *t* (t=1,…,104). The resulting data set is a panel with about 125,000 price quotes for each of the 104 months. The dataset also includes CPI weights, which are used to compute aggregate statistics.

Before calibrating the GTE sector shares and GC survival functions it is first essential to distinguish the concept of distribution of durations across contracts and the concept of distribution of duration across firms, which was first proposed by Dixon (2006). There is no difference between these two concepts in the traditional Taylor contract because in the Taylor type price setting the contract lengths are fixed and finished anyway. However, in the Calvo type price setting a fundamental difference can be found between these two concepts. According to Dixon and Kara (2006) the literature has wrongly used the distribution of duration across contracts as a way to measure nominal rigidity. The distribution of completed price spells across firms is the true way to count nominal rigidity. They define nominal rigidity as an individual firm setting the trajectory of its prices over time and they based this definition on the firm’s trajectory to count the average price duration. In this definition, the price duration should be measured on the firm’s level and not at the contracts level. The mean duration across firms is longer than that across contracts, which is also extensively shown in all the recent empirical and theoretical literature (Dixon and Kara 2006, Dixon and Le Bihan 2010).

Dixon (2010) links three representations of the same distribution, namely distribution of duration across firms, age distribution and hazard rate, into a unified framework. These three concepts in this unified framework can be easily transferred with each other. The hazard rate profile can be applied into the GC model and the duration across the firm concept is used to measure the sector shares in GTE. However, in practice these are just different ways of looking at the same data.

In addition, in order to compare the heterogeneous price stickiness and homogenous price stickiness, the homogenous price settings (Calvo, Calvo with Indexation and Taylor) have to be endowed with similar price stickiness consistent with heterogeneous price settings. For example, the Calvo reset probability, has, therefore, to match the average frequency of GC price setting. Simple Taylor fixed price duration should correspond to the weighted average of sectoral duration in GTE price settings.

2.4.1 Survival Function

In the Calvo style contract, in every period the proportion of firms will optimise their price when they receive some signals while ω is used to measure this reset probability and $(1-\omega)$ measures the remaining proportion who will not reset contracts. The hazard rate at a particular age is defined as the proportion of contracts at ages *i* that do not last any longer. Age can be considered as a snapshot of the economy. The existing contracts remain, which includes both completed and incomplete contracts of the whole economy at that point. Hazard rate can be defined in terms of the age distribution. This gives the following equation:

$$\omega_i = \frac{\alpha_i^A - \alpha_{i+1}^A}{\alpha_i^A} = \frac{\Omega_i - \Omega_{i+1}}{\Omega_i} \qquad (2.56)$$

where Ω_i is survival probability and α_i^A is age distribution.

The corresponding idea of a hazard rate is that of the survival probability, which means the probability at birth that the price survives for at least *i* periods. $\Omega_1 = 1$ means that all contracts survive at least one period (measured as beginning of period):

$$\Omega_i = \prod_{\kappa=1}^{i-1} (1-\omega_\kappa) \tag{2.57}$$

Σ_Ω denotes the sum of survival probabilities and its reciprocal $\bar{\omega}$, which is considered as the flow of new contracts.

$$\Sigma_\Omega = \sum_{i=1}^{N} \Omega_i$$
$$\bar{\omega} = \Sigma_\Omega^{-1} \tag{2.58}$$

The corresponding age profile $\alpha^A \in \Delta_M^{F-1}$ is given by:

$$\alpha_i^A = \bar{\omega} \cdot \Omega_i = \omega(1-\omega)^{i-1} \tag{2.59}$$

The above relationship can be explained as a proportion of ω will reset in period *i+1*, and a proportion (1-ω) will survive until *i+1*. The average length based on age distribution is 1/ω, which is the traditional way to measure nominal rigidity in the literature.

Figure 2.1 Survival Rate of French data

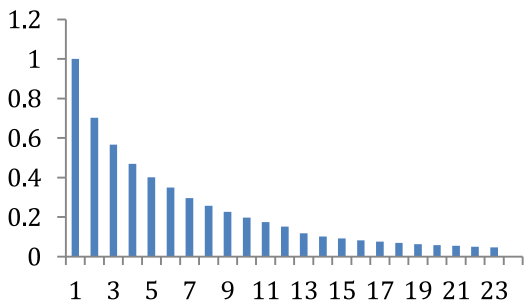


Figure 2.1 shows the monthly survival rate of price contracts in France and it assumes that all price contracts die at 24 months, which exhibits the exponentially decreasing pattern of weights as price-stickiness increases. The estimates are taken form Dixon and Le Bihan (2010). The survival rate estimated in SW (2003) is no longer used in order to compare the different price setting models under the same criterion. Instead, the transformed weighted average of the quarterly frequency which is derived from micro data evidence is applied to measure simple Calvo reset probability, which is found to be 50%.

2.4.2 The Distribution of Duration across Firm of Completed Contract Length

In Dixon(2006), the distribution of contract duration is measured based on firm level, the intuition behind this is that prices are set by firms and, consequently, the existing work based on price spell measure is wrongly measured by nominal rigidity, which is oversampling the shorter contracts in the economy that trigger an underestimate of nominal rigidity. In this 'firm-level' concept, each firm has an average contract length over period and the average contract length of the population of firms in the economy is the way to measure nominal rigidity.

The distribution of completed contract across firms (DAF) α_i corresponding to reset probability ω is:

$$\alpha_i = \bar{\omega} \cdot i \cdot \omega_i \cdot \Omega_i \qquad (2.60)$$

This one-to-one relationship between DAF and the hazard rate will generate the unique one-to-one relationship between DAF and age distribution:

$$\alpha_i = \omega_i i \alpha_i^A \tag{2.61}$$

α_i^A denotes cross section distribution of contract at given age *A* while α_i denotes cross section of contract ages at death (completed). The average length based on distribution of completed contract (DAF) is $2\omega^{-1} - 1$, which is almost twice as large as in distribution across contracts.

Figure 2.2 Distribution of Duration across Firms of Completed Contracts

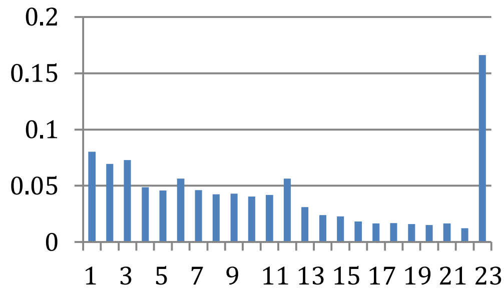


Figure 2.2 reflects the heterogeneity across sectors of price rigidity up to 24 months. This figure conveys the same information as the survival function in Figure 2.1. The shares of all of the other firms whose contract lengths longer than 23 months are all attached to 23 months because of the truncation of the distribution at 24 months. The mean duration of this distribution is approximately 3.87 quarters.

2.5 Model Analysis

The numerical method is used in this section to investigate the full model. In order to calculate the output gap in the Taylor Rule equation, the flexible part of this model also needs to be included. The model is solved and simulated using Dynare 4.2.1.

2.5.1 Calibration

The calibration of this model is mostly in line with SW (2003) because the model in this chapter is mainly based on their achievements. The only difference is in the calibration of the parameters concerning the heterogeneous of price stickiness, which has presented in detail in Section 2.4. An overview of all parameterisations is presented in Table 2.1.

Table 2.1 Parameter Values

Parameter	***Value***	***Interpretation***
α	0.3	Share of capital in total output
β	0.99	Time Discount rate
C_y	0.6	Steady-state consumption to GDP ratio
γ_w	0.763	Calvo Wage indexation to past inflation
γ_p	0.469	Calvo Price indexation to past inflation
G_y	0.18	Steady-state government expenditure to GDP ratio
h	0.573	Consumption habit persistence
I_y	0.22	Steady-state investment to GDP ratio
K_y	8.8	Steady-state capital stock to GDP ratio
λ_w	0.5	Mark-up in wage setting
φ	6.771	Inverse of elasticity of investment adjustment cost
ψ	0.169	Inverse of elasticity of capital utilization costs
$r_{\Delta\pi}$	0.14	Inflation growth parameter
$r_{\Delta y}$	0.159	Output gap growth parameter
ρ	0.961	Lagged interest rate parameter
r_π	1.684	Inflation parameter
r_y	0.099	Output gap parameter
$\bar{r}^k$	0.035	Steady state return on capital
δ	0.025	Depreciation rate
σ_c	1.353	Relative risk aversion
σ_l	2.4	Inverse of elasticity of labour supply to real wage
ϕ	1.408	One plus fixed cost in production
ξ_p	0.5	Calvo price survival rate
ξ_w	0.737	Calvo wage survival rate

Throughout the simulation, the discount factor β is 0.99, which implies a steady state annualised real interest rate of 4%. The Cobb-Douglas capital share parameter is 0.3, which corresponds to a steady state share of capital income in total output equal to roughly 30%. The depreciation rate δ equals to 0.025, which implies an annual rate of depreciation rate of capital equal to 10%. The wage markup rate λ_w is fixed to 0.5 since this parameter is not identified in the estimation procedure in SW(2003). CEE (2005) found that the impulse response functions implied by the model are insensitive to the values of λ_w. The elasticity of labour supply $1/\sigma_l$ is well within the range of point estimates reported in the labour literature (Rotemberg and Woodford 1999). The reset probability of wage resetting $1-\xi_w$ is assumed to be 0.263 in every period, implying that an average contract length based on the completed contract is more than 6.6 periods. Meanwhile, the quarterly constant probability determining the degree of price stickiness in Calvo price setting ξ_p is 0.5, which implies that the average price contract duration of completed contract is approximately 4 periods. This is consistent with steady state distribution across firms of completed contracts, which are used in GTE, and the hazard function, which is used in GC. Hence, in this study the initial simulations use the model exactly as in this literature except for the addition of different price settings; therefore, the sole effect of comparing the different price setting can be gauged.

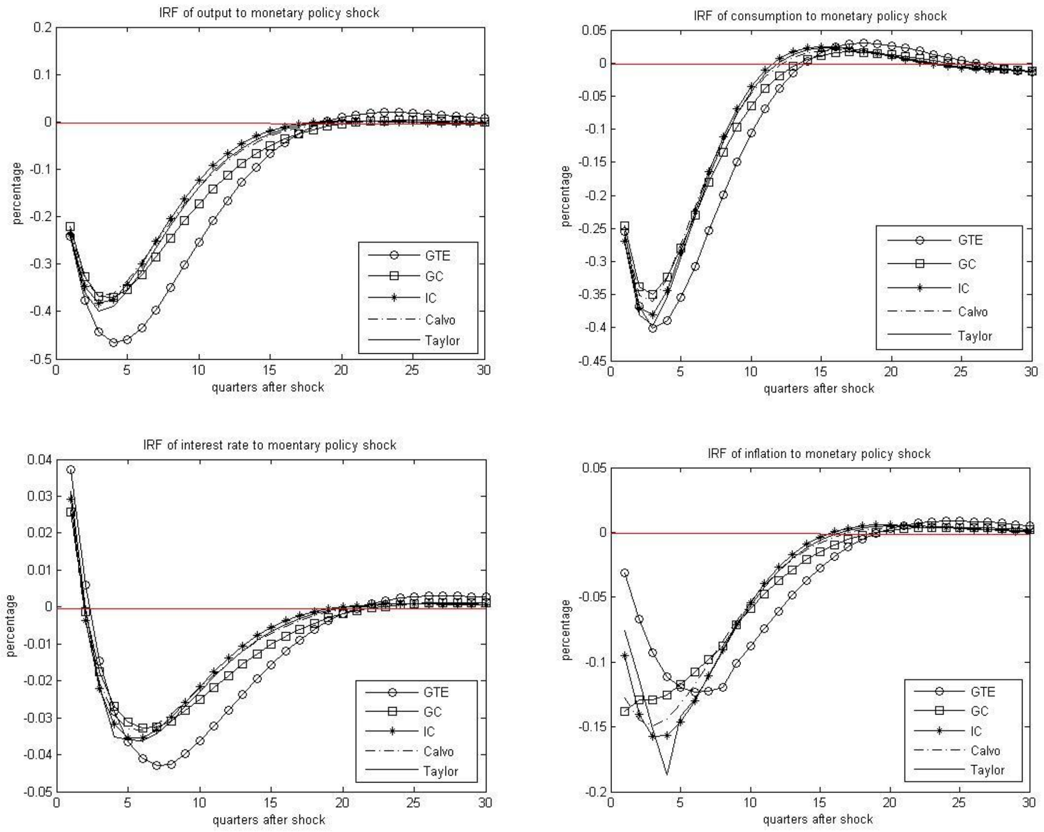
2.5.2 Impulse Response Functions (IRFs) Analyses

Since the model is largely in line with SW (2003), which has already been analysed in great detail, this chapter is mainly concerned with the particularities arising from the introduction of heterogeneity in price stickiness. Previous qualitative and quantitative results on this topic (Dixon and Kara 2005; Carvalho 2006; Dixon and Kara 2006; Jiang 2009; Dixon and Kara 2010; Dixon and Le Bihan 2010) indicate that monetary shocks tend to have more persistent real effects in heterogeneous economies when compared with homogeneous firms' economies with similar degrees of nominal and real rigidities. The intuition behind this is that heterogeneity in the contract lengths naturally leads to differences across sectors in the speed of adjustment to a shock. In turn, the resulting changes in the cross-sectional distribution of sectoral prices during the adjustment process have non-trivial aggregate effects. Consequently, in this section the key object of interest is to look at how the inclusion of heterogeneous price setting behaviour in the model affects the persistent real effect of a tightening monetary shock as well as affecting a positive technology shock on the main macro variables. The simulations' results will be presented graphically. This chapter will focus on productivity and monetary policy shocks.

First to be assumed is an unanticipated monetary policy tightening, which is associated with a temporary increase in the nominal and real interest rate. In the literature this has a hump-shaped negative effect on both output, consumption and inflation (Smets and Peersman 2001).

In order to illustrate how the inclusion of heterogeneous price stickiness in the fully specified SW model will better explain inflation and output persistence, Figure 2.3 below shows the main macro variables to a negative monetary policy shock under different price settings (simple Taylor economy with 4 periods of price stickiness, GTE with 8 sectors, GC with 8 sectors, simple Calvo with 0.5 reset probability and also Calvo with Indexation) in the fully specified SW benchmark model.

Figure 2.3 IRFs of Negative Monetary Policy Shock to Main Variables



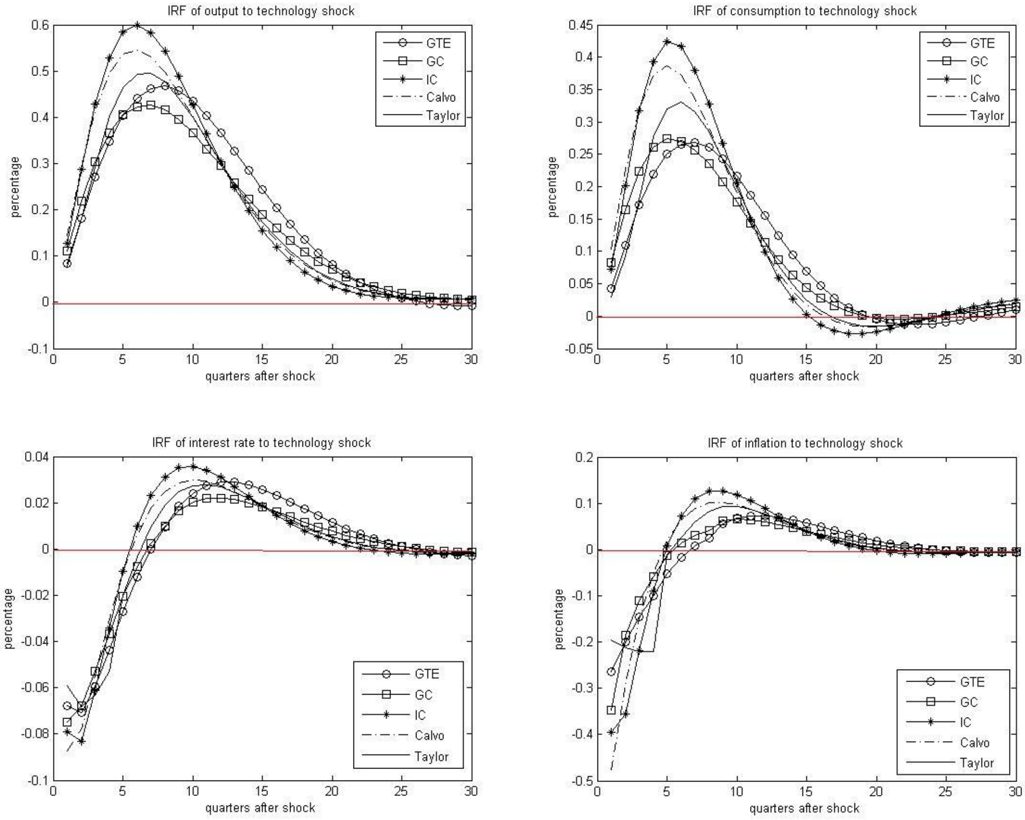
As can be seen in upper left graph in Figure 2.3, the heterogeneous price stickiness models GTE and GC generate a persistent response in output, with the peak response occurring after 4.5 quarters. Comparison with the homogeneous price settings GC generates the most persistent effect, which presents a more prolonged effect on output in the sense compared with other price setting who goes back to equilibrium after roughly 20 quarters. GTE does similar work as GC with a relatively faster dying out effect. Turning to the homogeneous price setting models, Calvo with indexation price setting shows a similar impulse response function as 4-period simple Taylor price setting as well as simple Calvo price setting model, which quickly go back to equilibrium after 15 quarters. From this point of view, the inclusion of indexation scheme to Calvo contract cannot improve the model's performance to match the empirical output persistence followed by a monetary shock.

Focus on the monetary policy shock on inflation, there is a hump-shaped effect in GTE, 4-period Taylor, simple Calvo, and Calvo with indexation price setting models, however, the GC model cannot capture inflation hump-shaped dynamics. In GTE price setting model, the peak effect of decrease in inflation roughly at 7 quarters after the monetary policy shock, while in other three homogenous price settings the policy shock impact peaks at roughly 3.5 quarters and then dies out in the following 10 quarters. To combine the impulse response functions of monetary policy shock on output and also inflation, the GTE price setting model shows that the peak effect of response of inflation to monetary policy shock delayed about 2.5 quarters of which output, which is in line with the empirical findings in CEE (2005).

The intuition behind this is due to the heterogeneity in the price stickiness structures. After a heterogeneous economy is hit by a shock, the initial adjustment process is driven mainly by sectors whose contract length is short, which happens since the majority of price changes are undertaken by firms in these sectors. As time passes, the distributions of price durations among firms become progressively dominated by firms in sectors with relatively longer contract length. The longer contract can hold the aggregate price in some extent even though the longer contract has a lower share of the total economy. This in turn influences the shorter contracts decision since when shorter sectors renew their prices they will take the expected future general price index into consideration. Short contract sectors dominate the earlier part of the adjustment process, whereas longer contract sectors subsequently drive most of the dynamics. As a result of this, the dynamic response of a heterogeneous economy to a nominal disturbance can differ from the response of an identical economy in which all firms have the same contract length, which endows the heterogeneous economy with the ability to display more persistent dynamics in response to monetary shocks. The reason why the heterogeneous price stickiness does not show the remarkable difference from identical economy (as demonstrated in Dixon (2010) and Jiang (2009)) is due to the small number of sectors and short price durations that are included in the model, which is only 8 sectors and the longest 8 periods price duration are taken into consideration. Including more sectors and longer contracts in the heterogeneous economy will be the future interest of research when the data is available.

Secondly, assuming there is a positive technology shock, it will trigger an increase in output and consumption as well as which it will have a negative hump-shaped effect on interest rate and inflation. Figure 2.4 below shows the impulse response functions produced by a positive temporary productivity shock.

Figure 2.4 IRFs of Technology Shock to Main Variables



In all price setting cases, a positive productivity shock leads to a gradual increase in output and consumption but it has a negative impact on interest rate and inflation rate. The marginal cost falls on impact due to the rise in productivity. Inflation falls gradually since monetary policy does not respond strongly enough to offset this fall in marginal cost. The difference in the magnitude and persistence of the reaction to the technology shock over different price settings can be seen in Figure 2.4. The initial responses of the all price setting models are fairly similar to each other; however, as time goes by, the GTE and also GC price settings show more output persistence than those homogeneous price settings. Unlike the monetary policy shock that hit the economy where the heterogeneous price setting has a stronger reaction and also a longer effect in main macro variables, a temporary technology shock does not trigger a big effect in the heterogeneous economy but still can generate longer persistence effect than homogeneous price settings which can be seen in Figure 2.4 that GTE and GC price setting model exhibit relatively longer and fatter tails of IRFs.

The mean lag $\sum_{j=0}^{\infty} j \cdot k_j \Big/ \sum_{j=0}^{\infty} k_j$ (Dotsey and King 1996) is used to calculate in order to make the results more robust and considerably easier to compare, where k_j measures the impulse response coefficients for output at lag j. The mean lag is measured as the weighted average of the time path.[5]

Table 2.2 Summary of the Persistence Measure of a Tightening Monetary Policy Shock

	GTE	***GC***	***IC***	***Calvo***	***Taylor***
Output persistence	5.92	6.34	5.62	5.91	5.61
Inflation persistence	6.45	5.38	4.82	4.90	4.81

Table 2.2 summarises the persistence measure in the face of a negative monetary policy shock under different price settings. The focus is on output and inflation persistence, which is the widely interest element for monetary policy makers and theorists. Firstly, when focusing on the measure of output persistence, the mean lag of the output response of GTE is longer than that from 4-period simple Taylor. GC performs better than conventional Calvo and Calvo with indexation price settings. In particular, GC generates the highest output persistence compared with all other price setting models. The reason why GC produces more output persistence than GTE is due to the essence of the Calvo contract in that GC are more forwarding looking while

[5] The number of periods used in this chapter to measure the impulse response is 30 quarters, which is long enough to measure for the responses and adding more quarters do not significantly affect the results.

GTE are more myopic when resetting prices (Dixon 2010) and, therefore, GC can produce marginally higher output persistence than the GTE. Focusing on the homogeneous Calvo price settings, the results show that indexation cannot better generate output persistence than conventional Calvo price setting. This finding coincides with the results reported in SW (2007) which find that the inclusion of indexation scheme in both price and wage setting cannot improve the model's performance.

Furthermore, in explaining inflation persistence in the face of monetary policy shock, GTE produces the best result among all the cases. In addition, GTE is the only model to catch the feature that the response of inflation will be more delayed than that of output. Although due to the different structures of GTE and GC they have some different performance to match the stylised fact of the economy, generally speaking, these heterogeneous price settings which share the same steady state distribution derived from micro data evidence can improve the model's performance compared with homogenous price settings. In addition, the widely used ad hoc Calvo with Indexation price setting cannot improve the model's performance in explaining the persistence issue relative to the conventional Calvo price setups. In summary, those pricing structures that are compatible with the heterogeneous price stickiness derived from micro data evidence, GTE and GC can significantly improve the output and inflation persistence relative to the homogenous price settings.

2.6 Conclusion

This chapter has first reviewed the characteristics of the New Keynesian Model and the performance of the NNS model in the recent literature. The review has shown that in the conventional time-dependent price settings the simple Calvo and simple Taylor cannot capture the real business cycle phenomenon. Some form of extension that is based on these nominal rigidity setups is widely developed in the literature. One of the most important extensions is Calvo with indexation price settings, which assumes that those agents who cannot reoptimise their price will partially or entirely update with inflation. Although the ad hoc indexation setups can help the conventional time-dependent model to capture the main macro variable dynamics successfully (SW 2003), this ad hoc extension is at odds with the real micro data since in reality price cannot change every period. In addition to this criticism, the ample evidence of recent research on micro price data shows that price stickiness does not stay constant across products and, based on these findings, the heterogeneous price setting models (GTE, GC) were established by Huw and Kara (2005, 2006, 2010, 2011), Wolman(1999) and Dixon and Bihan (2010). In GTE price setting model, there are several sectors in the economy and each sector has its own specific fixed price duration. This setup can includes the conventional simple Taylor price setting as a special case that there is only one sector with only one price duration in the economy. The other heterogeneous price setting is GC in which the reset probability is no longer a constant rate but depends on how long the price lasts. Both of these two different heterogeneous price settings share the same steady state distribution of price duration. Specifically, GTE differs across section while GC differs across time span.

Based on the substantial volume of research on the empirical micro evidence on measuring price rigidity, the micro data evidence is directly applied into the macro models. By applying the survival function derived from the French CPI data set in GC price setting (Dixon and Le Bihan 2010), the corresponding duration across firm of completed contract are calculated and is used in measure the sector's shares in GTE. The SW (2003) DSGE model was then extended into another dimension, which combines the recent insights from micro price data evidence into a macro model in order to evaluate the impact of heterogeneity in the price stickiness on the model's dynamics. The obtained impulse response of output and inflation from a tightening monetary policy shock and the corresponding measure of mean lag both show that incorporating heterogeneity in price stickiness can substantially improve the model's performance relative to the conventional homogeneous price settings.

In particular, the GC model has a longer tail of the impulse response of output to monetary policy shock, which indicates the higher output persistence. Meanwhile, GTE can better generate the inflation inertia and GTE is the only model that can fit the co-movement pattern of inflation and output. Furthermore, the results also show that extending the ad hoc indexation to past inflation to conventional Calvo price setting does not significantly improve the persistence measure, which is contrary to the findings of SW (2003) but which is in line with the results in SW (2007). Overall, to incorporate heterogeneous price stickiness into a macro DSGE model can better explain the real business phenomenon.

Because of the lack of micro price evidence, there are only 8 sectors are considered into modelling heterogeneous price setting. Truncating the tail of price distribution at 23 months induce the higher share in longer price duration sector (the 8th sector) which in turn distort to calculate the true mean price duration of the whole economy and the higher proportion of longer price contracts in the economy can significantly influence the performance of GTE price settings. Thus, including more micro price evidence and corresponding longer price durations in the economy to see how small proportion of longer price contracts can generate inflation and output persistence are the interest for future research. Besides that, wage stickiness is also a very important feature to influence the performance of sticky price rigidity regime in matching the data. Thus, investigating micro wage data and applying it into corresponding heterogeneity in wage stickiness is also worthwhile of further research. In this chapter, all five price setting models can successfully generate the hump-shaped impulse response functions followed by a monetary policy shock and also a technology shock (in this thesis, we only focus on analysing these two important shocks, in future research, the analysis of other structural shocks like markup shocks will also be taken into consideration), besides the existence of price and wage stickiness in the model, the incorporation of habit formation in consumption also plays an important role in generating this important feature. In order to isolate the effect how nominal rigidity incorporated in the model to influence the model's performance, for future research, excluding the habit persistence in consumption can better examine to what extent price and wage rigidity can help model to generate the hump shaped impulse response of output and inflation persistence.

Appendix 1

From the first order condition with respect to L_t^τ and C_t^τ in household optimisation:

$$\partial C_t^\tau : \lambda_t = U_{c,t} = \varepsilon_t^B \cdot \left(C_t^\tau - H_t\right)^{-\sigma_c}$$

$$\partial L_t^\tau : \lambda_t \cdot W_t^\tau = U_{l,t} = \varepsilon_t^B \cdot \varepsilon_t^L \cdot \left(L_t^\tau\right)^{\sigma_l}$$

$$\Rightarrow W_t^\tau = \frac{U_{l,t}}{U_{c,t}} = \frac{\varepsilon_t^L \left(L_t^\tau\right)^{\sigma_l}}{\left(C_t^\tau - H_t\right)^{-\sigma_c}} \tag{2.62}$$

This should then be log-linearised, which yields the 'shadow wage':

$$\hat{W}_t^* = \sigma_l \hat{L}_t^\tau + \frac{\sigma_c}{1-h}\left(\hat{C}_t^\tau - h \cdot \hat{C}_{t-1}^\tau\right) + \varepsilon_t^L \tag{2.63}$$

A.1.1 GTE Wage-setting

If the household-union knows the length of its contract to be *i* periods, then the reset wage X_{it}^w will fulfil $W_{t+i}^\tau = X_{it}^w$ for $i = 1, ..., N$. The optimal reset wage is obtained by maximising the intertemporal utility function subject to this structure of wage stickiness and a standard budget constraint. In log-linear form the optimal reset wage is given by:

$$\hat{X}_{it}^w = \left(\frac{1}{\sum_{i=1}^N \beta^{i-1}}\right) \sum_{i=1}^N \beta^{i-1} E_t \hat{W}_{t+i-1}^* \tag{2.64}$$

That is, $\hat{X}_{it}^w$ is a weighted average of the discounted nominal shadow wages W_{t+i-1}^*.

The aggregate wage is related to the sectoral wages W_{it} , where the weights α_{iw} come from the cross-sectional distribution across firms in the data. The sectoral wages W_{it} are simply an average across past reset wages in that sector:

$$W_{it} = \frac{1}{i}\sum_{i=1}^{N} X_{i,t+i-1}^{w} \tag{2.65}$$

The aggregate wage in GTE is given as follows:

$$W_t = \sum_{i=1}^{N} \alpha_{iw} W_{it} \tag{2.66}$$

A.1.2 GC Wage-setting

Under the Generalised Calvo wage setting model, the reset wage is given as:

$$X_t^w = \frac{1}{\sum_{i=1}^{N} \Omega_i \beta^{i-1}} \sum_{i=1}^{N} \Omega_i \beta^{i-1} W_{t+i-1}^{*} \tag{2.67}$$

That is, the optimal reset wage is a weighted average of the discounted nominal shadow wages.

The aggregate wage is the average of past reset prices, weighted by survival probabilities:

$$\hat{W}_t^{GC} = \bar{\omega} \sum_{i=1}^{N} \Omega_i \hat{W}_{w,t-i+1}^{GC} \tag{2.68}$$

Chapter 3 Testing the Smets-Wouters Model with the Heterogeneous and Homogeneous Price Settings of France by Using Indirect Inference

3.1 Introduction

Chapter 2 has suggested that the introduction of heterogeneous price stickiness can improve the performance of NNS model to better explain the real effect of business cycle phenomenon with consistent micro data evidence. This chapter will move from model simulation to model evaluation. The aim of this chapter is to use a novel evaluation method to test a standard calibrated New Keynesian model with different representations of price settings, which are: Calvo with partial indexation, Generalised Calvo (GC), Generalised Taylor Economy (GTE) contract, and also conventional Calvo and Taylor contract, respectively. This is done to determine which price setting behaviour can replicate the dynamics and size of the real French data best by using indirect inference method.

Smets and Wouters (2003) has become the workhorse of the recent DSGE model because of their notable contribution to explaining many important macro issues. Smets and Wouters (2003) propose a DSGE model of the Euro area and estimate by using Bayesian methods after allowing for a full set of pre-specified, but ad hoc, stochastic shocks. The results show that this DSGE model which is incorporated many nominal and real rigidity features is superior in performance to both a Bayesian and a standard VAR. However, this is questioned by the recent work by Meenagh, Minford et al.(2008) whose results find that by using indirect inference method to test this DSGE model that it is incapable of replicating the actual data's dynamic performance and the model generates excessive variance compared with real data. In addition, Dixon and Le Bihan (2010) point out that the price and wage setting in this model (which is modelled as Calvo contracts and follow an ad hoc backward-looking indexation mechanism) is not consistent with the micro data in reality.

Based on the better performance of heterogeneous price setting models in Chapter 2, the main question arises: even if the best price setting model is discovered, it might not be able to be used in practice, so it has to use the empirical evidence to evaluate the performance of different price settings against the data. There are two main aspects of this chapter. Firstly, the other two New Keynesian heterogeneous price settings are introduced in the model to compare with different homogeneous price settings and to find whether the heterogeneous price stickiness can explain the real data better empirically and to discover what kind of price setting model is required to fit the data. The GTE price setting allows for different sectors in the economy and each sector has its own specified fixed Taylor type contract. In the GC price setting the reset probability in Calvo contract is no longer a constant and this value changes as the duration of contract differs. The introduction of these two heterogeneous price settings takes the empirical micro price evidence from recent literature to feature the distribution of price stickiness consistently. Secondly, by using the new evaluation procedure to review the model's performance, this chapter looks at whether the simulated data from a calibrated structural model, treated as the null hypothesis, can explain the actual data which is represented by the dynamic behaviour of a well-fitting auxiliary model such as a VAR. The test here, which is in the form of a Wald test, focuses on the overall capacity of the model to fit the data's dynamic performance. Based on the testing results, a general idea among these different price settings in the DSGE model can be made and which price setting model performs better can be also determined.

The proposed way to testing the price setting model is to set up different structural models, which only differ in the price setting part. They are then compared according to their ability to replicate the dynamic behaviour of the data. A common metric is then be used to assess the fitness of each model to the dynamic facts of real data. Among these five variants, if one model passes the test, which means that this structural model and its corresponding price setting is well specified. The testing results show that the heterogeneity in price stickiness model can better fit the data behaviour than homogenous price settings.

The rest of this chapter is organised as follows. Section 3.2 is a literature review of the work evaluating the standard New Keynesian DSGE models and also on the application of the indirect inference method. The description of the methodology in Section 3.3 gives the details of the testing procedure while data description and standard parameter calibration are presented in Section 3.4. A comparison and discussion of the testing results based on different price settings are given in Section 3.5. Finally, Section 3.6 concludes and summarises the chapter.

3.2 Literature Review

Both CEE (2005) and SW (2003) examine the empirical fitness of New Keynesian DSGE models under imperfect competition where prices and wages are modelled by

Calvo type contract with an indexation mechanism. CEE (2005) demonstrates that this model is able to fit: the dynamic responses in the U.S. data, the observed inertia in inflation and persistence in output, as well as the hump-shaped responses to monetary policy shocks. Meanwhile, SW (2003) uses a Bayesian estimation technique which shows that the model is able to fit the unconditional moments in the Euro area data as well as predicting comparably to conventional theoretical VARs, with a sufficient number of structural shocks incorporated in the model. Although their estimation methods differ, the models are all reasonably similar. Both incorporate an ad hoc indexation scheme, although CEE (2005) assume full indexation while SW (2003) assume partial indexation.

There already exists a large body of work devoted to carrying out tests on whether or not the structural model can fit the dynamic facts of the real data. The usual method to test if the DSGE model captures the real business cycle effect is to compare the correlations in the actual data with the average correlations produced by the model's dynamic simulations. Meanwhile, the average is computed from the repeated dynamic simulations over a sample period which is derived by drawing repeatedly from the model's shocks. Since the focus of these models is on the business cycle, the data and the model's shocks are both detrended in some way. Christiano and Eichenbaum (1992), Burnside, Eichenbaum et al. (1993), and Feve and Langot (1994) have all evaluated the performance of their DGSE models by using a Wald test to check whether or not the model's selected moments are statistically different from those in the data. Diebold, Ohanian et al. (1998) evaluate the performance of a model by using the data's sampling variability to investigate whether the model's second moments lie within a prespecified confidence interval of the distribution of these moments, which is constructed by resampling the actual data.

Another method that uses the simulation variability from the structural model to construct the distributions of moments of interest is to test whether the corresponding moments in the actual data lies within these distributions at some level of confidence (Gregory and Smith 1991; Soderlind 1994; Cogley and Sbordone 2008). Other related approaches are to compare the spectra and cross-spectra for particular groups of variables in the data. In addition, the Impulse Response Functions (IRFs) of the data and the model for particular shocks and groups of variables are also used to compare. In order to do all these comparisons in moments, cross-spectra, or IRFs for particular groups of variables, there is a need for a global metric to evaluate the comparison of the model with the data and the corresponding criterion of rejection need to be set. In response to this need, other work has developed measures of a model's overall 'distance' from the data. The first such work was done by Watson (1993) who found that different models can then be ranked according to this distance. SW (2003, 2007) was interested as Bayesians in combining the best features into an improved model based on the posterior finding of distance.

Minford, Theodoridis et al. (2007) then established a new evaluation method which they called 'indirect inference', to take the whole model as the null hypothesis to investigate the whole model's ability to explain the particular features of the economy. The basic idea is to set the structural model, *M*, as a null hypothesis, which is regarded as the true description of the data and, therefore, its structural residuals can be considered as the true errors. Under this null, the random parts of the residuals are bootstrapped and the model is simulated with these random errors to generate a large number of sample replications. An auxiliary model, *T*, typically a VAR, is then chosen for the actual data sample so that it describes the data closely and parsimoniously. Consequently, this independent 'auxiliary model' is used as a bridge to connect to estimate and test the structural model. The implications of *M* for the *T* under the null hypothesis of *M* is true, can be discovered by estimating the same VAR on each of the simulation-sample generated from the structural model, which can be used to generate the distribution of the VAR's parameters according to the structural model. Then the VAR estimated on the actual data sample can be tested to find out whether or not it lies within this distribution at some confidence level.

Meenagh, Minford et al. (2008) test the SW (2003) model by using the indirect inference method. They shows that, unlike the successful performance as in SW (2003), this DSGE model which features nominal and real rigidities and full sets of structural shocks fails to pass the Wald test, even at a 99% confidence interval. This paper has also tested the counterpart of the New Keynesian model, the New Classical flexible economy model, and they find that it is still rejected at some confidence interval. At the end of this paper, they construct a hybrid price setting model of New Keynesian and New Classical and base on this hybrid price setting, the model passes the test. Furthermore, Le, Meenagh et al. (2008) have used the same method to test SW (2007) model for the U.S. economy, the model again fails the test. The most important feature in SW (2003, 2007) is Calvo with Indexation price setting. The failure of these models might demonstrate that the current price settings are not appropriate to mimic the real world price strategy, which should be found at elsewhere.

Throughout this thesis five models which only differ in their price setting part are presented. Hence, by comparing the capacity of these five variants it can be determined that which one fits the real data best implies that the price setting can provide the best explanation for 'reality' and, therefore, is the most appropriate description of price rigidity.

3.3 Methodology

Put briefly, indirect inference originally uses as an estimation method whose essence is to use the auxiliary model which is independent of the structural model to describe the real time-series data and it estimates the parameters of the structural model to find which model can indirectly replicate the behaviour of the auxiliary model most accurately according to a criterion of 'closeness' (Gregory and Smith 1991; Gourieroux, Monfort et al. 1993). This method can also be used to evaluate the behaviour of structural models whose structure is much closer to that specified by the theory. In effect, this arrests the method before estimation proceeds further.

For the purposes of model evaluation, the parameters of the macroeconomic model are given—either already estimated or calibrated. The aim of this chapter is to compare the auxiliary model based on two sets of data (i.e. the observed data and the data simulated from bootstrapping the structural disturbances) and to find whether the estimates of the auxiliary model based on the simulated data derived from the given calibrated structural model can statistically match the those based on the real data. From the simulation, the joint distribution of the parameters of auxiliary model can be obtained and used to perform a Wald test.

VAR is usually chosen as the auxiliary model and VAR (1) on a limited number of key variables is used as the beginning of the test. VAR coefficients summarise various aspects of the data, which are the partial effects in statistical terms. The diagonal terms measure the partial autocorrelation of one variable or its own persistence effect. For example, the partial autocorrelation of inflation measures the extent to which if a shock occurs to inflation alone it would persist in next period's inflation, while the off-diagonal terms measure the partial cross-effects of variables. While it is usual to compare data and model outcomes in terms of total correlations, this alternative approach gives another method to measure the statistical relationships into their partial components.

Raising the order of the VAR and increasing the number of variables increases the stringency of the overall test of the model. When the structural model has already rejected by a VAR (1) then there is no need to proceed to a higher order VAR. Non-rejection of the null hypothesis (structural model) means that the dynamic behaviour of the macroeconomic model is not significantly different from that of the observed data. Rejection means that the macroeconomic model is incorrectly specified by the tests.

Assuming that the macroeconomic model forms a system of equations, which concerns the whole class of structural macroeconomic models, the model can be generally represented as follows:

$$y_t = f\left[y_t, y_t(L), x_t, x_t(L), y_t^e, y_t^e(L); \theta; \varepsilon_t \right] t = 1, 2, \ldots, n$$

where y_t is the vector of the endogenous variables, x_t is that of the exogenous variables, (L) is the lag operator, y_t^e is the vector of expectations, θ is the structural parameters, and ε_t is the vector of structural equation errors. The null hypothesis assumes that the structural model is correct and, therefore, the errors in the structural model on the right hand side are considered as true values.

Step 1: Estimate of the errors of the economic model conditional on the actual data and structural parameters $\hat{\theta}$.

The structural model is solved in this step and the structural errors ε_t implied by the theory are calculated from the real data and structural model parameters $\hat{\theta}$.[6] It is usually assumed that the dimension of the vector of the stochastic processes ε_t that governs the system is the same as the dimension of the vector of the observable variables y_t, which means the number of independent structural errors is taken to be less than or equal to the number of endogenous variables. Since the model is assumed to be true then these implied errors are true under null hypothesis. Because of the identification problem to proceed indirect inference evaluation, ten structural shocks are reduced to seven, which enter the equation of monetary policy reaction function, the production function, wage setting, Euler equation, investment, equity and good markets clear condition.

Step 2: Bootstrap simulations.

Structural errors ε_t are modelled by autoregressive processes of i.i.d. shocks ε_t^* which are then extracted as the residual from their autoregressive processes. Simulations based on the structural model are then generated from this by using standard resampling techniques for i.i.d. data. The empirical distribution of endogenous variables y_t conditional on the structural model can then be approximated through each bootstrap. The bootstraps in the test are all drawn as time vectors so that any contemporaneous correlation between the residuals will be preserved.

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[6] The structural errors are calculated by directly backing out from the equations and data, the method which is used to calculate the expectations in the structural model is the robust instrumental variables estimation suggested by McCallum (1976) and Wickens (1982), which advises that the lagged endogenous data are set as instruments and the fitted values are calculated from a VAR(1).

Step 3: Wald statistic.

An auxiliary model as an independent model is introduced in this step, following Minford, Theodoridis et al.(2007). The auxiliary model takes VAR(1) form, which includes five main macro variables (i.e. interest rate, output, inflation, consumption, and investment) into consideration. A Wald statistic is then used to end this test to check whether the joint set of auxiliary model parameters $\hat{\gamma}$ estimated on the real data lie within the 95% intervals of the distribution for γ which is obtained from the sampling distribution. This joint distribution is shown in Le, Meenagh et al. (2008) who report that it has quite good accuracy in small sample Montecarlo experiments. [7]

To obtain the individual parameter confidence interval of γ, the two 2.5% bootstrap tails for each needs to be taken individually. The joint confidence interval for the whole set of γ requires the bootstrap combinations for γ to be ordered around their mean. To establish this ordering, the square of the Mahalanobis distance can be calculated as:

$$\left(\hat{\gamma}-\gamma^{o}\right)'\Sigma_{\gamma}^{-1}\left(\hat{\gamma}-\gamma^{o}\right) \qquad (3.1)$$

where $\hat{\gamma}$ is the vector of the VAR coefficients based on each simulated data, γ^{o} is vector of the estimates' means based on the simulated data, and Σ_{γ} is a variance-covariance matrix of $\hat{\gamma}$.

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[7] Le, Meenagh et al. (2008) show that the bias due to bootstrappling was just over 2% at 95% confidence level, and 0.6% at the 99% confidence interval.

The bootstrapping proceeds by drawing N bootstrap samples of the structural model, and then estimating the auxiliary VAR on each, thus obtaining $N\ \hat{\gamma}$. This set of vectors represents the sampling variation implied by the structural model, enabling its mean, variance-covariance matrix, and confidence bound to be calculated directly. N is generally set to 1,000. Then there will be 1,000 Mahalanobis distance that are ordered in ascending distance to construct the confidence interval. The Wald statistic is then calculated as the percentile value of $\hat{\gamma}$ estimated on auxiliary model T in terms of the above bootstrap distribution in order to find whether or not to fall in the critical percentile value because it can then be chosen as the rejection boundary. This tests whether the observed dynamics and volatility of the chosen variables are explained by the simulated joint distribution of the corresponding parameters at a given confidence level. If the distance of the actual parameter is in a percentile higher than 95th of that ordering then it means that the model is rejected at the 95% level of confidence.

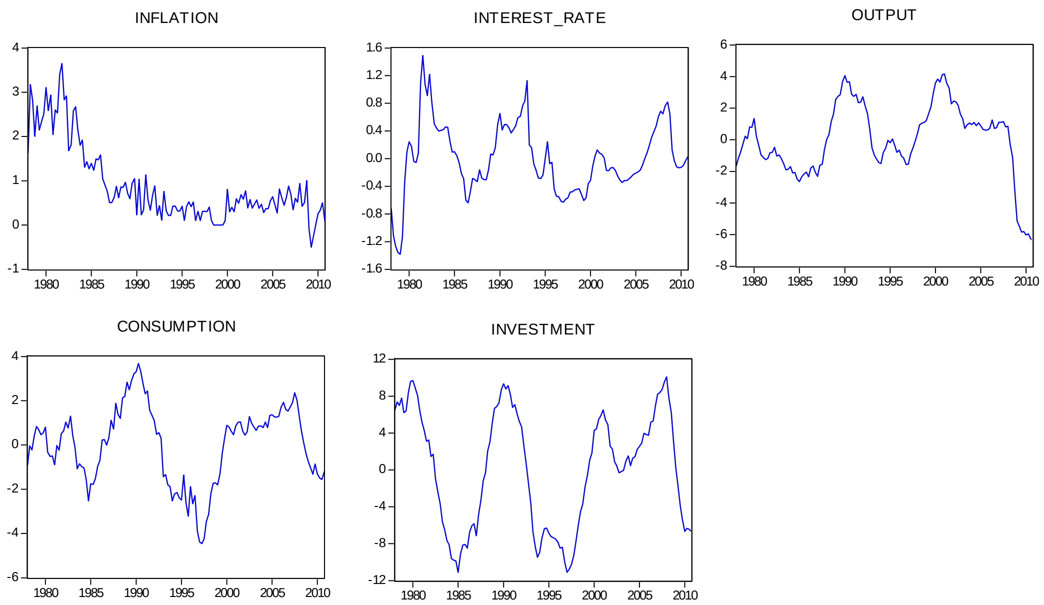
3.4 Data and Calibration

3.4.1 Data

This thesis employs the quarterly data published by OECD and National Institute of Statistics and Economic Studies (France) from 1978Q1 to 2010Q4 (which covers all of the available data set of the French economy) to test the different price setting models in the French economy.

Regarding those endogenous variables involved in the structural model, a linear detrend method is used to ensure the stationarity of all the real data used. The advantage of this method is that it can better preserve data information by excluding the trend component than other alternatives such as the HP-filter which excludes too much information in the data. It is especially important to note that output y_t, consumption c_t, and investment i_t are measured by the percentage deviations from their corresponding linear trends. Meanwhile, the interest rate r_t measures as the deviation of current short term interest rate from the steady-state value and π_t is defined as the log difference between the current CPI and its one period lagged term. The linear detrended time series are plotted in Figure 3.1.

Figure 3.1 Detrended Series of Main Endogenous Variables



The relevant unit root test results are presented in Table 3.1, which shows that all five observables have passed the ADF test at 5% significant level.

Table 3.1 Unit Root Tests for Stationarity

Time Series	*5% Critical Value*	*ADF test stats*	*p-values*
π_t	-1.9434	-2.2264	0.0256
r_t	-1.9434	-3.9842	0.0001
y_t	-1.9434	-2.0312	0.0409
c_t	-1.9434	-2.3819	0.0172
i_t	-1.9434	-3.5695	0.0004

Note: Mackinnon(1996) one-sided p-values are reported.

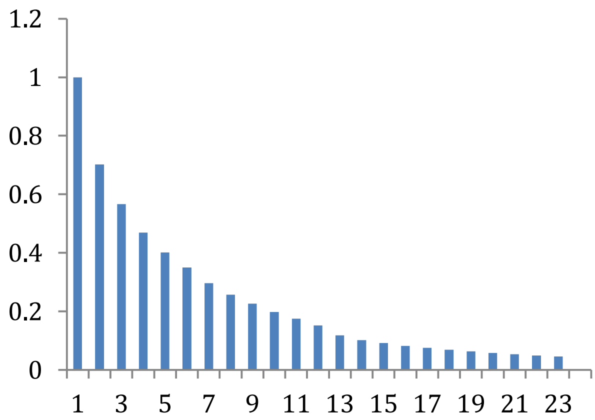
3.4.2 Calibration

3.4.2.1 The distribution of heterogeneous price stickiness

In order to calibrate the parameters to measure heterogeneous price stickiness in GTE price setting, the share of different sectors in the economy can be measured by the distribution of completed contract lengths across firms. This concept argues that the literature which uses the distribution of durations across contracts to measure nominal rigidity is incorrect since firms act as a price setter who sets the trajectory of prices over time and it should be taken to measure price rigidity from firm level. Thus, the mean durations over firms are longer than that over the contracts. The distribution of durations across firms α_i is used to measure the heterogeneous price rigidity in GTE price setting. The duration dependent reset probability profile ω_i is used to calibrate the GC price setting. Dixon (2010) developed a unified framework to link the distribution of durations across firms and the implied duration-dependent reset probability profile of the same distribution. Once one distribution is known then the other can be easily derived from the representations. In this thesis, the micro evidence of the French economy that was collected by Baudry, Le Bihan et al. (2007) is used , details of the calibration of the French micro data is shown in Dixon and Le Bihan (2010).

Figure 3.2 shows the monthly survival rate of price contracts in France and it assumes that all price contracts die at 24 months (equivalent to 8 quarters), which exhibits the exponentially decreasing pattern of weights as price-stickiness increases. In order to compare the different price setting models under the same criterion, the survival rate estimated in SW (2003) is no longer used while the transformed weighted average of the quarterly frequency derived from micro data evidence is applied to measure simple Calvo reset probability, which is 50%.

Figure 3.2 Survival Rate of French Data



3.4.2.2 Structural model parameters

The calibrated value of common parameters that is used in all these price setting models is taken as the value of posterior mean based on the Bayesian estimation results of Smets and Wouters (2003) in the literature.[8] The quarterly discount rate β is 0.99, implying that the approximately 1% quarterly interest rate is in a steady state. The depreciation rate δ is 0.025, which implies an annual depreciation rate of 10%. The values of σ_c and σ_l are set as 1.353 and 2.4, respectively, which indicates the elastic of both intertemporal consumption decision and labour supply estimated on the Euro data. The Calvo wage stickiness is 0.737, which implies that the average wage contract length of completed contracts is more than 6 quarters, while the wage mark-up is set as a constant value as 0.5. According to the micro CPI data reported in Baudry, Le Bihan et al. (2007) and Dixon and Bihan (2010), the corresponding average quarterly survival rate of price is 0.5, which indicates that the average price duration of completed contracts in France is approximately 4 quarters. With regard to the monetary policy rule, the interest rate's response to a unit change in inflation and output gap are 1.684 and 0.099, respectively. The high degree of interest smoothing parameters is 0.961.

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[8] For more detail see Table 2.1.

3.5 Testing the Results — An Application

Since the SW (2003) model has been carefully estimated on the Euro data from a well established micro foundation, and the results shows a good report to fit the data, this can be considered as a good starting point for this new, novel evaluation method. In this section the indirect inference testing procedure is applied to the SW (2003) framework with difference price settings by using the French macro data from 1978Q1 to 2010Q4. The data series are detrended as in SW (2003), which is obtained by taking the deviation of all of the variables from a mean and a linear trend. Dynare 4.2.1 is used to solve the model (Juillard 2001). The structural parameters' parameterisation begins from the original SW model using their Bayesian estimate posterior means (SW 2003). This is combined with seven observable data (i.e. output, real wage, consumption, investment, labour, interest rate (rate per quarter), and inflation (quarterly rate)) in order to proceed the testing procedure (capital stock, equity returns and capacity utilisation are all constructed variables by using model's identities). The variables which are included in the auxiliary model VAR(1) are five main macro variables (i.e. output, investment, consumption, interest rate and inflation rate) which, apart from the constant, yields 25 VAR coefficients.[9]

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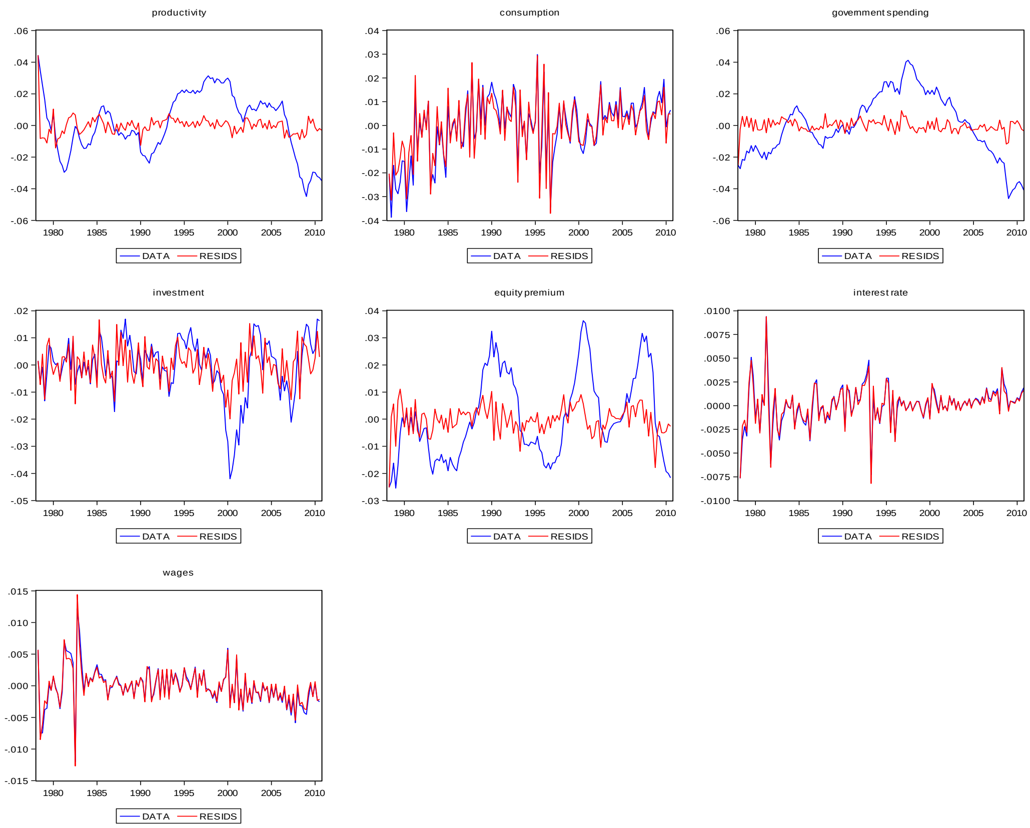
[9] Since all of the variables included in the auxiliary model VAR(1) are mean deviations, there is no constant includes in the autoregressive coefficient matrix.

3.5.1 The actual disturbances implied by the model compared with the assumed errors

The starting point to precede the evaluation of the indirect inference is to use the structural model's residuals to do a bootstrap to get the simulated data from the structural model. The residuals are derived by using the observed data and the expected variables in each model equation. The exact way to derive these structural residuals is to back them out of the equations by using the real data and given structural parameters. The sample for both bootstraps and data estimation was 132 observations (i.e. 1978Q1 to 2010Q4).

In the original SW (2003) framework the wage setting equation and monetary policy function include two structural shocks in one equation, which cannot be identified simultaneously. Consequently, in this section the number of shocks is reduced to the number of observables in the model (SW 2007). There are seven errors, which are: productivity, consumption, government spending, investment, equity premium, interest rates and wage markup. The results of the residuals calculated from the above procedure are shown below in Figure 3.3.

Figure 3.3 Single Equation Errors from Structural Model



The structural residuals implied by the data and model equations are derived and the new autoregressive parameters of the error process are re-estimated. Table 3.2 below shows the comparison between SW's assumed shocks and the generated shocks derived from the French data. The AR coefficients of the structural residuals show a very different pattern between data generated and SW estimates. The estimated residuals for consumption and investment shocks exhibit markedly less persistence than SW assumed. In addition, the Equity Premium shock is highly persistent and does not have zero AR coefficients as assumed in SW (2003). The standard deviations of the estimated error innovations (which are reported in the parentheses) are almost larger than those estimated in SW (2003).

Table 3.2 AR Coefficients of Shocks and Variances of Innovations (SW vs. Data Generated)

AR Coefficients	*SW*	*Data Generated*
Productivity	0.823 (0.598)	0.9914 (0.8802)
Consumption	0.855 (0.336)	0.5524 (0.2596)
Government Spending	0.949 (0.325)	0.9920 (0.4228)
Investment	0.927 (0.085)	0.3603 (0.5313)
Equity	0 (0.604)	0.9232 (0.4912)
Interest Rate	0 (0.081)	0 (0.2111)
Wage	0 (0.289)	0 (0.2795)

3.5.2 Evaluating the SW Model with Calvo with Indexation Price Setting

After re-estimating the error processes with new autoregressive parameters by using the French macro data the next step is to bootstrap the innovations' random components and draw them as vectors to preserve any dependence between them. Since there are five endogenous variables (i.e. interest rate, output, consumption, investment and inflation) in the VAR (1) representation, there are 25 individual VAR coefficients involved in Table 3.3. Together with the model simulated 95% upper and lower bound, Table 3.3 reflects whether or not the estimates of the VAR parameters individually lie within the 95% confidence intervals as implied by the structural model. The estimates of those VAR parameters represent the partial regressors of each variable on the lagged values of itself and the others. One of the ways to make a comparison here is to count how many of these regressor estimates individually reject the structural model.

Table 3.3 Individual VAR Coeffs based on IC price setting

VAR Coeffs	*Actual Estimate*	*95% Lower Bound*	*95% Upper Bound*	*State*
A_R^R [10]	0.879390	0.219481	0.830757	out
A_Y^R	0.004051	-0.153400	0.033163	in
A_C^R	-0.011138	-0.037281	0.071062	in
A_I^R	0.005509	-0.004711	0.040528	in
A_π^R	-0.007705	0.039792	0.230482	out
A_R^Y	-0.442315	-2.921323	-0.737512	out
A_Y^Y	0.978999	0.404886	1.065254	in
A_C^Y	0.056980	-0.171292	0.239461	in
A_I^Y	0.021198	-0.010616	0.152024	in
A_π^Y	0.019380	-0.057343	0.653881	in
A_R^C	-0.236674	-4.166423	-0.528425	out
A_Y^C	0.009694	-0.750971	0.304561	in
A_C^C	0.936638	0.607077	1.287990	in
A_I^C	-0.010419	-0.066469	0.200458	in
A_π^C	0.016716	0.047010	1.201671	out
A_R^I	-1.279060	-5.189727	0.535025	in
A_Y^I	0.115378	-1.397390	0.660775	in
A_C^I	-0.009020	-0.615547	0.745594	in
A_I^I	0.923159	0.833485	1.330428	in
A_π^I	-0.050816	-1.062027	0.797897	in
A_R^π	-0.033057	-2.198965	-0.202138	out
A_Y^π	-0.010158	-0.555691	0.082292	in
A_C^π	0.021340	-0.125070	0.292335	in
A_I^π	0.012210	-0.013352	0.146845	in
A_π^π	0.935758	0.939048	1.552233	out
Wald Stats	100%	***Normalised t-stats***	17.9663	

[10] The upper subscript denotes variables in the current period; the lower subscript denotes variables in the one lagged period.

According to Table 3.3, out of the 25 real-data-based estimates of the VAR coefficients, 7 are found to lie outside their corresponding 95% bounds that are implied by the structural model. Specifically, the model implied inflation produces a little bit higher persistence when compared with the real data while the real data based interest rate exhibits more interest rate smoothing pattern than the 95% lower and upper bounds from the structural model simulation. Meanwhile, the response of interest rate to lagged inflation and the response of output to lagged interest rate, as well as the response of inflation to lagged interest rate, that are predicted from the structural model are all shown to be more aggressive than that which the real data exhibits. In addition, the upper bound of model simulated consumption's response of lagged interest rate is more than twice as great as the real data based value. Overall, the Wald statistic is reported as 100%, which indicates the model fails at 95% confidence level while its Normalised Mahalanobis Distance[11] is 17.9663, indicating that the data's dynamic properties are not close to that implied by the model. This can be explained by the large numbers of the VAR's parameters that lie outside the 95% model implied bounds. Although this DSGE model cannot fit the data even in a moderate level, the main purpose of this thesis is to use this new method to rank the different price setting models to see whether or not one of models can stand out as relatively acceptable.

Turning to the other aspect of the concerned 'stylised facts', Table 3.4 below shows the extent of the observed volatilities of the real data which can be explained by the structural model:

[11] Normalised Mahalanobis Distance (Normalised t-stats) of the Wald percentile is calculated based on Wilson and Hilferty (1931)'s method of transforming a chi-squared distribution into a standard normal distribution. The formula: $Z=\left\{\left[\left(2M^{squ}\right)^{1/2}-\left(2n\right)^{1/2}\right]\Big/\left[\left(2M^{squ^{95th}}\right)^{1/2}-\left(2n\right)^{1/2}\right]\right\}\times 1.645$

where the M^{squ} is the square of Mahalanobis distance with actual data, $M^{squ^{95th}}$ is the 95% critical value based on the simulated distribution, n is the degrees of freedom of the variant.

Table 3.4 Volatilities of the Endogenous Variables based on IC price setting

Volatilities of the endogenous variables	*Values calculated with real data*	*95%Lower Bound*	*95%Upper Bound*	*State*
Var(R_t)	0.0026	0.0034	0.0208	out
Var(Y_t)	0.0530	0.1297	2.5818	out
Var(C_t)	0.0299	0.1438	1.7721	out
Var(I_t)	0.4057	2.2728	34.8699	out
Var(π_t)	0.0078	0.0343	0.2446	out
Directed Wald Statistics(for volatilities)	60.2%	***Normalised t-stats***	0.0960	

Table 3.4 shows that all of these five endogenous variables (i.e. interest rate, inflation, output, investment and consumption) are individually out of the 95% model's implied bounds. The model cannot replicate the data quite well, which produces generally excess variance of interest rate and too much excessive variances of output, consumption, investment, and inflation. The Wald Statistics is 60.2%, which indicates that although individually the observed volatilities of the data are not in the 95% bounds, they can be explained jointly by the structural model.

The above two tables (i.e. Table 3.3 and Table 3.4) report the structural model's partial capacities in explaining either the dynamic or volatilities of the actual data. In order to evaluate the model's overall fitness to the real world it is possible to combine both the dynamic and volatilities simultaneously. The results of this test are reported below in Table 3.5, which is still 100% rejected. Hence, the null hypothesis that the theoretical model is true is rejected at 95% confidence level, and even at the more tolerant 99% confidence interval. The reason that the structural model fails to pass the test is because it generates excessive variances compared with the real data and also because of its failure to pick up lagged response at the individually coefficients level.

Table 3.5 Full Wald Statistics for IC price setting

	Full Wald Statistics	***Normalised t-stats***
Dynamics + Volatilities	100%	16.1780

In summary, the SW Euro model fails in several important ways to match the French data, especially in its overall fitness in explaining the data. The reason why this model generates results that are quite different from the SW (2003) evaluation results might come from the drop in persistence of the actual demand shocks compared with SW's assumed shocks as well as the high persistence in the equity premium shock. In addition, the different data sources may be another reason for the different results.

3.5.3 Evaluating the SW Model with Generalised Calvo Price Setting

In this section the Generalised Calvo price setting (GC) is introduced in the SW model, leaving the other economic environment unchanged. In the GC price setting, the hazard rate is no longer a constant term as in conventional Calvo price setting; on the contrary, the hazard rate differs in the duration of price. The longer the price spells, the higher the hazard rate. The calibration of this heterogeneous price stickiness is derived from micro CPI data evidence of France. GC price setting can better explain the real world price stickiness since the Calvo price setup including the fraction of price will survive forever which is unrealistic, while GC not only generalises that the different price duration has a different price reset probability but it also limits the price duration to a more reasonable length. Since in this thesis the durations of price is truncated at 24 months, at a quarterly horizon, therefore, there are a total of 8 quarters with 8 different hazard rates in the economy.

Table 3.6 Individual VAR Coeffs based on GC price setting

VAR Coeffs	*Actual Estimate*	*95%Lower Bound*	*95%Upper Bound*	*State*
A_R^R	0.879390	0.548919	0.911394	in
A_Y^R	0.004051	-0.097576	0.050093	in
A_C^R	-0.011138	-0.035596	0.053403	in
A_I^R	0.005509	-0.006868	0.026059	in
A_π^R	-0.007705	0.019245	0.138362	out
A_R^Y	-0.442315	-2.250996	-0.702304	out
A_Y^Y	0.978999	0.520205	1.063029	in
A_C^Y	0.056980	-0.133835	0.198744	in
A_I^Y	0.021198	-0.008257	0.125548	in
A_π^Y	0.019380	0.040801	0.525572	out
A_R^C	-0.236674	-3.089380	-0.579354	out
A_Y^C	0.009694	-0.523817	0.389719	in
A_C^C	0.936638	0.601446	1.182861	in
A_I^C	-0.010419	-0.086062	0.140040	in
A_π^C	0.016716	0.039463	0.990936	out
A_R^I	-1.279060	-4.206373	0.248928	in
A_Y^I	0.115378	-1.472496	0.472176	in
A_C^I	-0.009020	-0.423679	0.863112	in
A_I^I	0.923159	0.892882	1.348746	in
A_π^I	-0.050816	-0.690614	0.714724	in
A_R^π	-0.033057	-0.746170	0.666495	in
A_Y^π	-0.010158	-0.358924	0.331910	in
A_C^π	0.021340	-0.211959	0.263508	in
A_I^π	0.012210	-0.080285	0.092255	in
A_π^π	0.935758	0.562198	1.055269	in
Wald Stats	100%	***Normalised t-stats***	8.9046	

In GC price setting model, 5 out of 25 VAR coefficients lie outside of the 95% simulated bound. Compared with the Calvo with Indexation price setting model, it can be seen that the GC can better capture not only these partial regressor estimates individually but it can also do so jointly. The GC can capture both the inflation persistence and interest rate smoothing pattern successfully when compared with the Calvo with Indexation price setting model. However, the response of the interest rate to lagged inflation, the response of output to lagged interest rate as well as to lagged inflation, and consumption's response to the interest rate are all less aggressive than the model stimulated bound, respectively. The overall Wald Statistics is 100%. Although the GC price setting model is rejected even at the 99% confidence level, the Normalised Mahalanobis Distance is equal to 8.9046, which is much lower than the Calvo with Indexation price setting model.

Table 3.7 below reports the model's ability to explain the volatilities of the main endogenous variables in the structural model. Like the Calvo with Indexation price setting model, simulated data from the structural GC price setting model still generate too much excessive variance in output, consumption, investment and inflation, but it reasonably matches the series of interest rate variances. Although the variances of the real data cannot individually be captured by the model-implied 95% bounds, the Wald Statistics for the volatilities part is 49.5%, which means that GC price setting model can jointly explain the variances of main endogenous variables in the structural model.

Table 3.7 Volatilities of the Endogenous Variables based on GC price setting

Volatilities of the endogenous variables	*Values calculated with real data*	*95%Lower Bound*	*95%Upper Bound*	*State*
Var(R_t)	0.0026	0.0022	0.0231	in
Var(Y_t)	0.0530	0.0843	2.7604	out
Var(C_t)	0.0299	0.1198	1.7738	out
Var(I_t)	0.4057	1.5587	32.5410	out
Var(π_t)	0.0078	0.0159	0.2057	out
Directed Wald Statistics(for volatilities)	49.5%	***Normalised t-stats***	-0.0063	

For the Full Wald Statistics, Table 3.8 shows that the Wald Statistics is 100%. This means that the structural model cannot generate the joint distribution of both dynamics and volatilities that simultaneously explains those observed in reality. However, compared with the SW Calvo with Indexation price setting, the extent of rejection is lower. The Normalised Mahalanobis Distance can be used to measure this, which is from 17.9663 to 7.7207.

Table 3.8 Full Wald Statistics for GC price setting

	Full Wald Statistics	*Normalised t-stats*
Dynamics + Volatilities	100%	7.7207

In summary, the results are rather mixed. The model has failed on the VAR coefficients at the 95% confidence level, with a Wald Statistic of 100%. In addition, the model cannot reproduce the data variances for output, consumption, investment and inflation, all of these four data variances lie very far below the model’s lower bound. However, the joint Wald Statistics is 49.50, which has jointly captured the characteristics as shown by the real data.

3.5.4 Evaluating the SW Model with Generalised Taylor Economy Price Setting

This section introduces the GTE price setting into the model. This price setting assumes that there are many different sectors in the economy, and each sector has its own specified Taylor type contract. This heterogeneous price setting can better represent the real world price setting behaviour since real micro price evidence shows that prices indeed differ across different sectors in the economy.

Table 3.9 below summarises how the actual dynamics are explained by the structural GTE price setting model. The calculated 95% bounds for each individual estimate of the data descriptors are reported in all testing results tables, which show the data estimate for each descriptor lies within the model distribution for that descriptor alone. These may provide some hints to what aspects the model is misspecified. In total 3 out of 25 VAR individual coefficients lie outside the 95% range derived from the simulated data. The responses of investment to inflation and also to output are less aggressive than the model stimulated 95% upper and lower bound. The Wald Statistic reported is still as high as the previous two models at 100%, indicating that the structural model can hardly be used for explaining the observed dynamics jointly. The set of real data-based estimates of the VAR coefficients are not captured by the corresponding joint distribution generated from model simulation, even at the 99% confidence level.

Table 3.9 Individual VAR Coeffs based on GTE price setting

VAR Coeffs	*Actual Estimate*	*95%Lower Bound*	*95%Upper Bound*	*State*
A_R^R	0.879390	0.6998	0.9930	in
A_Y^R	0.004051	-0.1130	0.0601	in
A_C^R	-0.011138	-0.0420	0.0751	in
A_I^R	0.005509	-0.0101	0.0301	in
A_π^R	-0.007705	-0.0849	0.0855	in
A_R^Y	-0.442315	-0.4879	0.6077	in
A_Y^Y	0.978999	0.6615	1.1650	in
A_C^Y	0.056980	-0.1372	0.2098	in
A_I^Y	-0.021198	-0.0517	0.0693	in
A_π^Y	0.019380	-0.7768	-0.1471	out
A_R^C	-0.236674	-0.6216	-0.1646	in
A_Y^C	0.009694	-0.1223	0.1707	in
A_C^C	0.936638	0.8182	1.0263	in
A_I^C	0.010419	-0.0368	0.0345	in
A_π^C	0.016716	-0.0898	0.2277	in
A_R^I	-1.279060	-0.3657	3.9413	out
A_Y^I	0.115378	-1.2430	1.1111	in
A_C^I	-0.009020	-0.7926	0.9215	in
A_I^I	0.923159	0.6498	1.2511	in
A_π^I	-0.050816	-3.7139	-0.7228	out
A_R^π	-0.033057	-0.4588	0.0507	in
A_Y^π	-0.010158	-0.2397	0.1179	in
A_C^π	-0.021340	-0.1075	0.1450	in
A_I^π	0.012210	-0.0247	0.0640	in
A_π^π	0.935758	0.5943	0.9731	in
Wald Stats	100%	***Normalised t-stats***	12.0294	

Turning to the volatilities of the endogenous variables, Table 3.10 shows that the GTE price setting structural model has difficulties to mimicking the performance of output, consumption and investment as well as inflation, which generates too much variance as in the previous two models. The data variance for nominal interest rate is the only variable that can fit with the real data. The Wald Statistic is reported as 51.3%, which implies that the model can jointly explain the observed volatilities in a proper way.

Table 3.10 Volatilities of the Endogenous Variables based on GTE price setting

Volatilities of the endogenous variables	***Values calculated with real data***	***95%Lower Bound***	***95%Upper Bound***	***State***
Var(R_t)	0.0026	0.0023	0.0251	in
Var(Y_t)	0.0530	0.1029	2.1493	out
Var(C_t)	0.0299	0.1501	1.8922	out
Var(I_t)	0.4057	1.5884	29.4446	out
Var(π_t)	0.0078	0.0122	0.1710	out
Directed Wald Statistics(for volatility)	51.3%	***Normalised t-stats***	-0.0050	

Table 3.11 below reports the overall performance of the model. The GTE price setting model is still rejected at even a more tolerant 99% confidence level, with a little higher normalised t-stats value than GC, but it is still much lower than Calvo with Indexation price setting model.

Table 3.11 Full Wald Statistics of GTE price setting

	Full Wald Statistics	***Normalised t-stats***
Dynamics & Volatilities	100%	10.3954

The failure of the GTE (also GC) price setting models to pass the test can be might due to the lack of enough sectors exist in the economy. The evaluation results are impacted because in the GTE price setting model there are only 8 sectors in the economy and the longest price duration in the economy is 2 years (as measured in GC), which is far less than the actual price length in reality. Dixon (2006) demonstrated that even a smaller proportion of longer contracts existing in the economy can hold back the general price setting, which influences the firm's decision with short price contract. To including more sectors in the GTE price setting model and longer price spells in the GC economy can improve the model's explanatory power. Investigate more wide ranges of micro data evidence will be the interest of future research.

3.5.5 Evaluating the SW Model with Calvo Price Setting

The conventional Calvo type contract is also considered in order to compare the performance of heterogeneous price stickiness and homogeneous price stickiness. The constant reset probability of the price contract is the weighted average of duration dependent reset probability, which equals 50%.

Table 3.12 below reports the individual VAR coefficients from the real data, and also the simulated corresponding 95% upper and lower bound which is implied by the structural model with Calvo price setting.

Table 3.12 Individual VAR Coeffs based on Calvo Price Setting

VAR Coeffs	***Actual Estimate***	***95%Lower Bound***	***95%Upper Bound***	***State***
A_R^R	0.879390	0.439737	0.836695	out
A_Y^R	0.004051	-0.119884	0.033126	in
A_C^R	-0.011138	-0.033989	0.059119	in
A_I^R	0.005509	-0.005177	0.031635	in
A_π^R	-0.007705	0.041853	0.157313	out
A_R^Y	-0.442315	-2.414541	-0.875779	out
A_Y^Y	0.978999	0.517659	1.068139	in
A_C^Y	0.056980	-0.161459	0.184234	in
A_I^Y	0.021198	-0.011861	0.123691	in
A_π^Y	0.019380	0.024410	0.499463	out
A_R^C	-0.236674	-3.249291	-0.562587	out
A_Y^C	0.009694	-0.592802	0.343774	in
A_C^C	0.936638	0.615076	1.226279	in
A_I^C	-0.010419	-0.076264	0.163125	in
A_π^C	0.016716	0.105985	0.940126	out
A_R^I	-1.279060	-4.810499	-0.247907	in
A_Y^I	0.115378	-1.366283	0.643101	in
A_C^I	-0.009020	-0.590226	0.726774	in
A_I^I	0.923159	0.844224	1.320731	in
A_π^I	-0.050816	-0.737868	0.621680	in
A_R^π	-0.033057	-1.197070	0.241632	in
A_Y^π	-0.010158	-0.497353	0.156820	in
A_C^π	0.021340	-0.146706	0.288179	in
A_I^π	0.012210	-0.037232	0.125701	in
A_π^π	0.935758	0.762730	1.190626	in
Wald Stats	100%	***Normalised t-stats***	17.2916	

There are 6 out of 25 VAR individual coefficients which lie outside the 95% range derived from the simulated data. Specifically, the Calvo price setting model fails to generate the interest rate smoothing pattern which is shown in the real data. In addition, the response of the interest rate to lagged inflation, the response of output to the interest rate, the response of output to inflation, the response of consumption to the interest rate, and the response of consumption to inflation all show in the passive pattern in the data compared with the simulated bound. The Wald Statistics reported is still as high as in the previous models at 100%, indicating that the structural model can hardly be used for explaining the observed dynamics because the set of real-data-based estimates of the VAR coefficients is not captured by the corresponding joint distribution generated from model simulation, even at a 99% confidence level.

Turning to the volatilities of the endogenous variables, Table 3.13 shows that the Calvo price setting structural model cannot mimic all of these five endogenous variables, which generates too much variance. The Wald Statistic is reported as 60.7%, which implies that the model can jointly explain the observed volatilities in a proper way.

Table 3.13 Volatilities of the Endogenous Variables based on Calvo Price Setting

Volatilities of the endogenous variables	***Values calculated with real data***	***95%Lower Bound***	***95%Upper Bound***	***State***
Var(R_t)	0.0026	0.0032	0.0203	out
Var(Y_t)	0.0530	0.1178	2.5029	out
Var(C_t)	0.0299	0.1357	1.7216	out
Var(I_t)	0.4057	2.2010	33.3975	out
Var(π_t)	0.0078	0.0329	0.2333	out
Directed Wald Statistics(for volatility)	60.7%	***Normalised t-stats***	0.0999	

Table 3.14 reports the overall performance of the model. Calvo price setting model is still rejected at even more tolerant 99% confidence level.

Table 3.14 Full Wald statistics of Calvo Price Setting

	Full Wald Statistics	***Normalised t-stats***
Dynamics & Volatilities	100%	15.4730

The Calvo price setting model yields similar results as the Calvo with Indexation price setting model, which indicates that the inclusion of this ad hoc indexation scheme cannot better fit the data. In this thesis, one of the key parameters is quite different from the SW (2003) estimation results. In SW (2003) the survival rate of Calvo price setting is 0.908 (which is also contradicts with micro data evidence), which is even stickier than the survival rate of wage setting (0.737). This estimation results in some sense contradicts the literature that the wage is usually much stickier than price. In this section, however, the survival rate of Calvo price setting is from the micro data evidence, which is measured as the average frequency of price changes that derives from GC price setting behaviour. In order to evaluate the performance of the different price settings it is important to make sure that price rigidity is measured in the same dimension and same calibration framework. Therefore, the parameter to measure price stickiness needs to be consistent throughout the five variants. In this case, the calibration value of the survival rate of Calvo price setting from the French micro data evidence is only 0.5, which is more realistic than the SW (2003) estimation result.

3.5.6 Evaluating the SW Model with Taylor Price Setting

The Taylor price setting assumes that there is a fixed length of price duration and firms know this ex ante. The fixed length of Taylor contract is derived from the corresponding Calvo contract by using the formula $2\omega^{-1}-1$ in order to compare models in the same micro data foundation, which is approximately 4 periods.

Table 3.15 below summarises how the actual dynamics are explained by the structural 4-period Taylor price setting model. It shows that 6 out of the 25 real-data based estimates of the VAR coefficients that reflect the actual dynamics are found to lie outside of the corresponding 95% bounds that are implied by the theoretical model. Specifically, the response of investment to inflation is shown to be more passive than that predicted by the theoretical model. The Wald Statistic reported is still as high as the previous models at 100%, indicating that the structural model can hardly be used for explaining the observed dynamics because the set of real-data-based estimates of the VAR coefficients is not captured by the corresponding joint distribution generated from model simulation, even at a 99% confidence level.

Table 3.15 Individual VAR Coeffs based on Taylor Price Setting

VAR Coeffs	*Actual Estimate*	*95% Lower Bound*	*95% Upper Bound*	*State*
A_R^R	0.879390	0.5475	0.9118	in
A_Y^R	0.004051	-0.3773	0.4221	in
A_C^R	-0.011138	-0.2896	0.2098	in
A_I^R	0.005509	-0.0810	0.1056	in
A_π^R	-0.007705	-0.0772	0.6793	in
A_R^Y	-0.442315	-0.0164	0.4790	out
A_Y^Y	0.978999	0.4831	1.4101	in
A_C^Y	0.056980	-0.3847	0.1860	in
A_I^Y	0.021198	-0.1142	0.1050	in
A_π^Y	0.019380	-1.4318	-0.3780	out
A_R^C	-0.236674	-0.1686	0.7164	out
A_Y^C	0.009694	-0.7499	0.8645	in
A_C^C	0.936638	0.2665	1.2350	in
A_I^C	-0.010419	-0.2027	0.1686	in
A_π^C	0.016716	-1.9180	-0.0067	out
A_R^I	-1.279060	-0.1808	0.9785	out
A_Y^I	0.115378	-1.0663	0.8102	in
A_C^I	-0.009020	-0.5371	0.6232	in
A_I^I	0.923159	0.7521	1.1879	in
A_π^I	-0.050816	-2.3866	-0.5235	out
A_R^π	-0.033057	-0.0773	0.0454	in
A_Y^π	-0.010158	-0.1310	0.0903	in
A_C^π	0.021340	-0.0526	0.0814	in
A_I^π	0.012210	-0.0218	0.0272	in
A_π^π	0.935758	0.8091	1.0195	in
Wald Stats	100%	***Normalised t-stats***	19.6033	

Turning to the volatilities of the endogenous variables, Table 3.16 shows the 4-period Taylor price setting structural model generates too much variance of all these five endogenous variables. The Wald Statistics is reported as 83.3%, which implies that the model can jointly explain the observed volatilities in a proper way.

Table 3.16 Volatilities of the Endogenous Variables based on Taylor Price Setting

Volatilities of the endogenous variables	***Values calculated with real data***	***95%Lower Bound***	***95%Upper Bound***	***State***
Var(R_t)	0.0026	0.0069	0.0267	out
Var(Y_t)	0.0530	0.2504	2.5880	out
Var(C_t)	0.0299	0.4836	2.1749	out
Var(I_t)	0.4057	2.2235	31.6214	out
Var(π_t)	0.0078	0.0335	0.2214	out
Directed Wald Statistics(for volatility)	83.3%	***Normalised t-stats***	0.6214	

Table 3.17 reports the overall performance of the model. A 4-periods Taylor price setting model is still rejected at even more tolerant 99% confidence level with highest normalised t-stats among these different price setting models.

Table 3.17 Full Wald statistics of Taylor Price Setting

	Full Wald Statistics	***Normalised t-stats***
Dynamics & Volatilities	100%	16.7513

Table 3.18 below summarise the evaluation results of these five DSGE models, which only differs in the price setting behaviours. Hence, by ranking the models in terms of their ‘closeness’ to the real world, one will in effect be considering whether the observed data are more likely to have been generated with the heterogeneous price settings or homogeneous price settings. From Table 3.18, it can be seen that all of the

five different price settings in this DSGE framework are rejected. The Full Wald test statistic of 100% and the Normalised Mahalanobis Distance (which is reported in the parenthesis) indicate that the data's dynamic properties are not close to that implied by the model. Although all of these models are rejected, the Normalised Mahalanobis Distance can be used to find which is closer to the bound. From the results it can be determined that the GC and GTE price setting models performs better than homogeneous price settings. This means that this type heterogeneity introduced in the price setting equations can empirically improve the model's ability to match the data.

Table 3.18 A Summary of the Test Results

Models	***IC***	***GC***	***GTE***	***Calvo***	***Taylor***
Dynamics	100% (17.9663)	100% (8.9046)	100% (12.0294)	100% (17.2916)	100% (19.0633)
Volatilities	60.20% (0.0960)	49.50% (-0.0063)	51.70% (-0.0050)	60.70% (0.0999)	83.30% (0.6214)
Full	100% (16.1780)	100% (7.7207)	100% (10.3954)	100% (15.4730)	100% (16.7513)

To summarise, the first point to note is that all of the models are found to fail in terms of the overall Wald Statistics evaluation, whether at the default 95% which is used throughout or at the more tolerant 99% level of confidence. This can be seen from Table 3.3 to Table 3.17, which set out the key results for the VAR (1) equations and the scale of volatility of the data. The failure results of the VAR (1) representation of the data implies that higher order VARs introduce more complexity into the data description and higher threshold of the test which makes it harder to see the main features of the comparison between data and models. Therefore, there is no need to raise the order of VAR to precede more tests.

Inflation Persistence

'Inflation persistence' can be defined as the partial autocorrelation of inflation in the VAR. This is a natural place to begin in evaluating these models since much of their motivation has been to explain data persistence in inflation as well as output. In the real data this inflation persistence coefficients is found to be 0.936. This indicates that, statistically, inflation would be quite persistent, which means that it would not settle down very quickly. From the results of the five different price setting models it is found that the Calvo with partial indexation price setting cannot match the inflation persistence. Calvo with Indexation price setting model generate too much higher inflation persistence than the data-generated VAR, which indicates that the inclusion of indexation scheme cannot help to improve model to fit the empirical features in the data. The better way is to leave this friction out. The GC and GTE model generates nearly as much inflation persistence as the data-generated VAR.

Other Features of the VAR

By focusing on the transmission of interest rate shocks to output it can be seen that the data-based VAR that sets this cross-effect is -0.442315. This cannot be captured by the Calvo with Indexation price setting model whose mean cross-effect on VARs based on model-generated data from -2.921323 to -0.737512. In addition, the GC model cannot capture this cross-effect either, whose range is from -2.250996 to -0.702304. However, the GTE model can explain this transmission mechanism in a proper way.

The data based parameter is 0.87939 for the interest rate smoothing aspect, which shows a reasonable interest rate smoothing between the current period and its lag term. Both GC and GTE can capture this effect successfully, while the Calvo with indexation price setting model cannot capture this effect since the simulated bound from the structural model only gives a relative passive pattern from 0.219481 to 0.830757.

To focus on the transmission effect of inflation to interest rate, in the data the cross effect of inflation on interest rate is slightly negative at -0.008, only GTE price setting model can capture this cross negative effect. To compare the 95% simulated bound among different price setting models, the upper bound predicted from the GTE model is quite similar as the lower bound predicted from the Calvo pricing model, from this point of view, it can be seen that different price setting models imply different inflation dynamics and Taylor rule response endogenously to inflation dynamics. It also raises the questions that some persistence not only come from inflation dynamics but also from 'imposed' interest rate smoothing part. To investigate the effect of endogenous inflation dynamic is interest for future research. However, in this chapter, the main purpose is to introducing a novel evaluation method, indirect inference, to test whether the price and wage rigidity DSGE model can replicate the data behaviour, the focus is using the overall Wald statistics to test whether the theoretical DSGE model is true or not.

All in all, it can be summarised from this that the performance of the Calvo with Indexation model has moderate failure across several aspects of the transmission mechanism, while the GC and GTE price setting models have a considerable success both in explaining inflation persistence and interest rate smoothing patterns.

3.5.7 A Comparison of Different Variable Combinations of the Different Price Setting Models

This section considers the model's performance for particular aspects of the data using the directed Wald test. The method which is used here is to focus on the different variables combinations by applying the Directed Wald test. Table 3.19 reports the Wald Statistics by different variable combinations.

Table 3.19 reports the performance of the different models for particular aspects of the data when using the Directed Wald test which focuses on groups of different combination of variables. The results show that none of these different price setting DSGE models can better explain the consumption and investment process since all groups which include these two variables are rejected due to the difficulty of measuring consumption and investment. However, the performance of the models improves sharply when only focusing on the real variables. When the variables are restricted to output, inflation and interest rate (which are the key interest variables for policy makers), the GC price setting model passes this Wald test at 95% confidence level and the GTE price setting model passes in a more tolerant way at a 99% confidence interval. Although the homogeneous price setting still cannot pass the test, from the Normalised t-stats it can be seen that it improves considerably than those combinations that include consumption and investment. For individual variables, all of them passed the test at 99% confidence level. These results show that both GC and GTE price settings perform better than the homogeneous price settings. From this view, it is proven that incorporate the heterogeneous price sticky micro data into the macro model remarkably improves the performance of DSGE models.

Table 3.19 Directed Wald Statistic by Variable Combinations.

Variable Combinations	*IC*	*GC*	*GTE*	*Calvo*	*Taylor*
R,Y,C,I,π	100 (16.1780)	100 (7.7207)	100 (10.3954)	100 (15.4730)	100 (16.7513)
Y,C,I	100 (15.0394)	99.8 (6.6354)	100 (7.5399)	100 (14.3564)	100 (13.8594)
R,Y,C, I	100 (15.3406)	100 (7.2699)	100 (9.4384)	100 (15.2895)	100 (13.8452)
Y,C,I,π	100 (15.5891)	99.9 (6.1614)	100 (9.3062)	100 (14.7502)	100 (15.5829)
R,Y,π	100 (7.8684)	94.1 (1.5343)	98.5 (2.7054)	100 (4.8416)	100 (7.7494)
Y,π	100 (7.1081)	93.4 (1.0033)	98.0 (2.0861)	100 (4.7543)	100 (6.7997)
R,π	98 (3.2859)	94.3 (1.5489)	95.9 (1.8789)	98.2 (2.2662)	99.7 (4.9042)
R	95.4 (1.7897)	93.8 (1.0207)	65.3 (-0.3074)	93.7 (1.4831)	96.4 (3.2859)
Y	82.8 (0.4275)	73.3 (0.0687)	80.7 (0.2473)	78.7 (0.1719)	94.6 (2.2766)
C	67.9 (0.0636)	76.9 (0.2409)	84 (0.3797)	68.7 (0.0628)	98 (2.8703)
I	96 (2.0313)	91.2 (0.9177)	92.6 (0.9843)	96.8 (2.0254)	98 (2.9271)
π	97.1 (2.1959)	92.8 (1.2946)	66.5 (0.0464)	96.2 (1.8315)	97.2 (2.5767)

Note: The Normalised t-stats is reported in the parenthesis below the corresponding Wald statistics

3.6 Conclusion

In this chapter a new bootstrap method (which is based on the method of indirect inference) is used for testing and comparing different price setting DSGE models according to their dynamic performance. The essence of this method is the separation between the structural model as the null hypothesis and using the independent dynamic time series representation of the data (i.e. VAR). The model's errors are estimated and used for bootstrapping. The resulting pseudo-samples are then used to formulate the sampling distribution of the dynamic time series model. The test then consists of discovering whether parameters of the time-series model estimated on the actual data lie within some confidence interval of the model-implied distribution. A Wald statistic and the corresponding overall Normalised Mahalanobis distance are calculated as a common metric to rank the model's performance.

This method is applied to test five versions of the New Keynesian model with different price settings. This test is used to discriminate between the different models' capacities to embrace the dynamic behaviour of the data; particularly, the different price setting model under the New Keynesian framework. With regard to the dynamics of the data, the Wald statistic based on the auxiliary model VAR(1) parameters show that all of the models are massively rejected given the set of data. From the testing results focus on the volatility part of the data, all price setting models exhibit greatly excessive volatility (especially in consumption, investment, inflation and output) compared with the data. When the auxiliary model only includes the variables that policymakers are most interested in (i.e. output, inflation and interest rate) the GC price setting model can best replicate the data while the GTE price setting model passes the test at a more tolerant 99% confidence level. Turning to the homogeneous price setting models, the ad hoc indexation scheme applied in Calvo price setting model cannot improve the model's performance while the worst performance is given by the simple Taylor price setting model. These results suggest that introducing heterogeneity into the nominal price rigidity can improve the model's explanatory power than homogeneous price setting models.

Chapter 4 Using a Bayesian Estimation Method to Estimate the Heterogeneous and Homogeneous Price Setting DSGE Models

4.1 Introduction

This chapter focuses on comparing and estimating the different pricing mechanisms in the context of DSGE models for the French economy using a Bayesian approach, which has increasingly attracted the attention of economists studying monetary policy. Following CEE (2005) and SW (2003), the model that is used in this study features a number of frictions that appear to be necessary to capture the empirical persistence in the U.S. and main Euro area macroeconomic data. Many of these frictions have become quite standard in the DSGE literature. The model that incorporates a variable capital utilisation rate which is used by Greenwood, Hercowitz, and Huffmann (1988) and King and Rebelo (2000). The introduction of capital utilisation rate will make the capital services elastic, which helps to dampen the movements in marginal costs by reducing fluctuations in the rental rate of capital. It also helps to reduce the fall in labour productivity after a positive monetary policy shock. Put simply, it helps to smooth the adjustment of the rental rate of capital in response to changes in output. SW (2003) follows CEE (2005) by modelling the cost of adjusting the capital stock as a function of the change in investment. The incorporation of the investment adjustment cost into the model analysis is used to help capture the hump-shaped response of investment after the expansionary monetary policy shock. Since the fall in interest rate will induce a surge in investment, a higher elasticity of the cost of adjusting investment reduces the sensitivity of investment to the real value of the existing capital stock. Finally, the inclusion of an external habit persistence in consumption preferences helps to generate the hump-shaped response of positive monetary policy shock since in effect it replaces the level of consumption with its growth rate in the utility function.

The parameters in the model are estimated by using seven key macro-economic time-series in France (i.e. real GDP, real consumption, real investment, real wages, GDP deflator and nominal short-term interest rate) which can be considered as representative of the main economy in the Euro area. Following recent developments in Bayesian estimation techniques (Geweke 1999), the models in this chapter are estimated by minimising the posterior distribution of the model parameters based on the linearised state-space representation of the DSGE model.

This analysis mainly differs from SW (2003) is the price setting in the model. In this chapter, the heterogeneity in price stickiness which directly relates the micro-data into price setting equations is introduced. There are two main approaches which can represent the heterogeneity in the price settings. One is the GTE setting, which is developed by Dixon and Kara (2005). In this framework, there are many sectors in the economy, and in each sector, there exists a simple Taylor contract of specific price duration, which is in cross section dimension. Dixon and Kara (2011) points out that loss of heterogeneity in price-spells will underestimate the degree of price dispersion in the economy, which in turn influences the central bank to control price stability. The other is the GC setting (Wolman 1999, Dixon and Le Bihan 2010), which is in duration dimension. In this setting, the hazard rate is no longer used as a constant as in the simple Calvo contract, the hazard rate in this setting is duration dependent and different price duration has a different hazard rate. Although these two heterogeneous price settings both incorporate the micro data in consideration, their pricing behaviour is quite different. GTE is the generalised form of Taylor type contract while GC is the generalised form of Calvo type contract. In the Taylor based approach firms know the duration of price spell ex ante while in the Calvo based approach firms only know the distribution of possible price-spells durations, which means that Calvo type firms are more forward looking than Taylor types.

The micro data evidence that is used to calibrate in GTE as share of each sectors is the duration across firm of completed contracts. The micro data evidence which is used in GC is the survival function that differs in duration of price-spells, which have exactly the same distributions of price-spells in aggregate. The survival rate which is used in Calvo price setting model is derived from the average frequency of GC price setting model, which also share the same steady state distribution as GTE.

The Bayesian technique is used to estimate the NNS models, which can combine a sound, micro-founded structure which is suitable for policy analysis with a good probabilistic description of the observed data and good forecasting performance. The Bayesian estimation methodology provides a natural framework for testing by comparing the marginal likelihood of the various models. Seven key quarterly macro variables are used as observable variables, which are: real GDP, hours worked, real consumption, real investment, real wages, the log difference of the GDP deflator and the short-term nominal interest rate. Because of the identification problem, the number of shocks included in this chapter is the same as the number of observables used in the estimation. There are seven shocks, which are: productivity shock, preference shock, government expenditure shock, investment shock, equity premium shock, wage markup shock and monetary policy shock. This chapter seeks to estimate and compare the heterogeneity of price settings models which is consistent with the micro data with the homogeneous price setting alternatives. Firstly, the model of the posterior distribution is estimated by maximising the log posterior function, which combines the prior information on the parameters with the likelihood of the data. In the second step, the Metropolis-Hastings algorithm is used to get a complete picture of the posterior distribution and to evaluate the marginal likelihood of the model. Finally, the comparison of the performances between the heterogeneous models and homogeneous alternatives are analysed in the results section. The findings presented in this chapter indicate that the data strongly favours the GC model.

The rest of this chapter is organised as follows. Recent literature on this topic is briefly reviewed in Section 4.2. Section 4.3 describes the methodology that is used in this chapter. Following that, Section 4.4 explains the data and priors while estimation and comparison results are shown in Section 4.5. Finally, Section 4.6 concludes this chapter.

4.2 Related Literature

There are several ways of estimating or calibrating the parameters of a linearised DSGE model. For example, Geweke (1999) distinguishes between the weak and strong econometric interpretation of DSGE models: the weak econometric estimation method minimises the distance between empirical and theoretical moments of the data, which provides more robust estimators than full-information estimators; while the strong econometric estimation method provides a full characterisation of the observed data series based on the whole theoretical models. Maximum likelihood methods first solve the structural model into the reduced form equation in the predetermined variables, and then the model is written in state-space form. State equation is in the form of predetermined variables, the observation equation links the predetermined state variables to observables. The third step is to use a Kalman filter to form the likelihood function. Finally, the parameters are estimated by maximising the likelihood function. In the Bayesian estimation method, the likelihood function of the data is combined with prior distributions for the parameters of the model to estimate the mode of the posterior function by maximising the log posterior density function. This posterior distribution comes from Monte-Carlo Markov-Chain methods (i.e. Metropolis-Hastings algorithm).

There are three main advantages of the Bayesian estimation method. The first advantage is that the use of prior distribution allows the microeconometric studies and the previous macroeconometric studies to be brought into consideration, which provides a way to link the previous calibration-based literature. The second advantage is that this method can provide the valuable stable results when the sample of data is relatively small. The final advantage is that the Bayesian approach provides a way of evaluating fundamentally misspecified models, which can be done either by using the marginal likelihood of the model or Bayes factors. The marginal likelihood of a model is directly related to the predictive density function. The prediction performance is the natural criterion for validating models for forecasting and policy analysis.

Recently, much research work uses this strong econometric technique to estimate the DSGE model. For example, Rabanal and Rubio-Ramirez (2005) investigate the wage rigidity in explaining the dynamics of the U.S. economy using a Bayesian estimation method. In their paper, Rabanal and Rubio-Ramirez (2005) found that the indexation scheme incorporated in wage setting cannot help to substantially improve the fit of the data, they also found that there is high degree of price stickiness across models. The inclusion of both price and wage rigidities into the model perform better than the model with only price stickiness. Laforte (2007) compares the three different pricing mechanisms by using Bayesian technique and finds that the Wolman model with vintage-dependent contract structure model can provide a better fit of the U.S. data than the Calvo with Indexation price setups as well as the sticky information model. Dixon and Kara (2011) use Bayesian methods to compare different pricing models (GTE and MC) and find that the results favour GTE strongly provided that enough sectors are included in the economy.

4.3 Methodology

Bayes' rule is the beginning point of the fundamental rule of the Bayesian model. The key idea of Bayes' rule is that the probability of an event A given on event B depends not only on the relationship between events A and B but also on the marginal probability of occurrence of each event. This can be included into the Bayesian estimation field as the prior:

$$p(A,B) = p(A|B)\,p(B) = p(B|A)\,p(A) \Rightarrow p(A|B) = \frac{p(B|A)\,p(A)}{p(B)} \qquad (4.1)$$

where *P(A)* is the prior or marginal probability of *A*. It is 'prior' in the sense that it does not take into account any information about *B*. *P(A|B)* is the conditional probability of *A*, given *B*, which is also called the posterior probability because it is derived from or depends upon the specified value of *B*. *P(B|A)* is the conditional probability of *B*, given *A*, which is also called the likelihood. *P(B)* is the prior or marginal probability of *B*, which acts as a normalising constant.

This fundamental rule is widely applied into the estimation, prediction and comparison in Bayesian econometrics. By applying the Bayes' rule by changing the corresponding components, it becomes:

$$p(\theta|y) = \frac{p(y|\theta)p(\theta)}{p(y)} \Rightarrow \overbrace{p(\theta|y)}^{\textbf{\textit{posterior density}}} \propto \underbrace{p(y|\theta)}_{\textbf{\textit{likelihood function}}} \overbrace{p(\theta)}^{\textbf{\textit{prior density}}}$$

In this application procedure, event *A* can be considered as the parameter θ needed to estimate in the model and event *B* can be treated as the observable data *y*. The likelihood function, prior, and marginal probability all need to be known in order to get the posterior density of the parameters.

Prior probability is one of the key elements to get posterior distribution, which usually follows the rules as: the parameter ranging from 0 to 1 is usually assigned with beta distribution; the parameter defined over the whole real axis is assigned with normal distribution; while the positive parameter is assigned with gamma distribution. However, the standard deviation is usually assigned with inverted gamma distribution to guarantee the positive variance.

The other important component to get the posterior probability is to estimate the likelihood function. A Kalman filter is usually most often used to estimate the likelihood function if there are unobservable variables in the model. There are three basic steps to the use of a Kalman filter for estimation, as outlined below:

Step 1: Rewrite the system in the state space representation.

There are two basic components in a dynamic system: controls and states (both endogenous and exogenous). The endogenous states are actually predetermined controls. In DSGE models, the solution for control variables only depends on state variables (i.e. transition or policy equation). However, although some of the endogenous variables in the system are usually unobservable, they are related to some observable signals. It is easy to write down a measurement/state equation bridging unobservables (x_t) with observables (y_t).

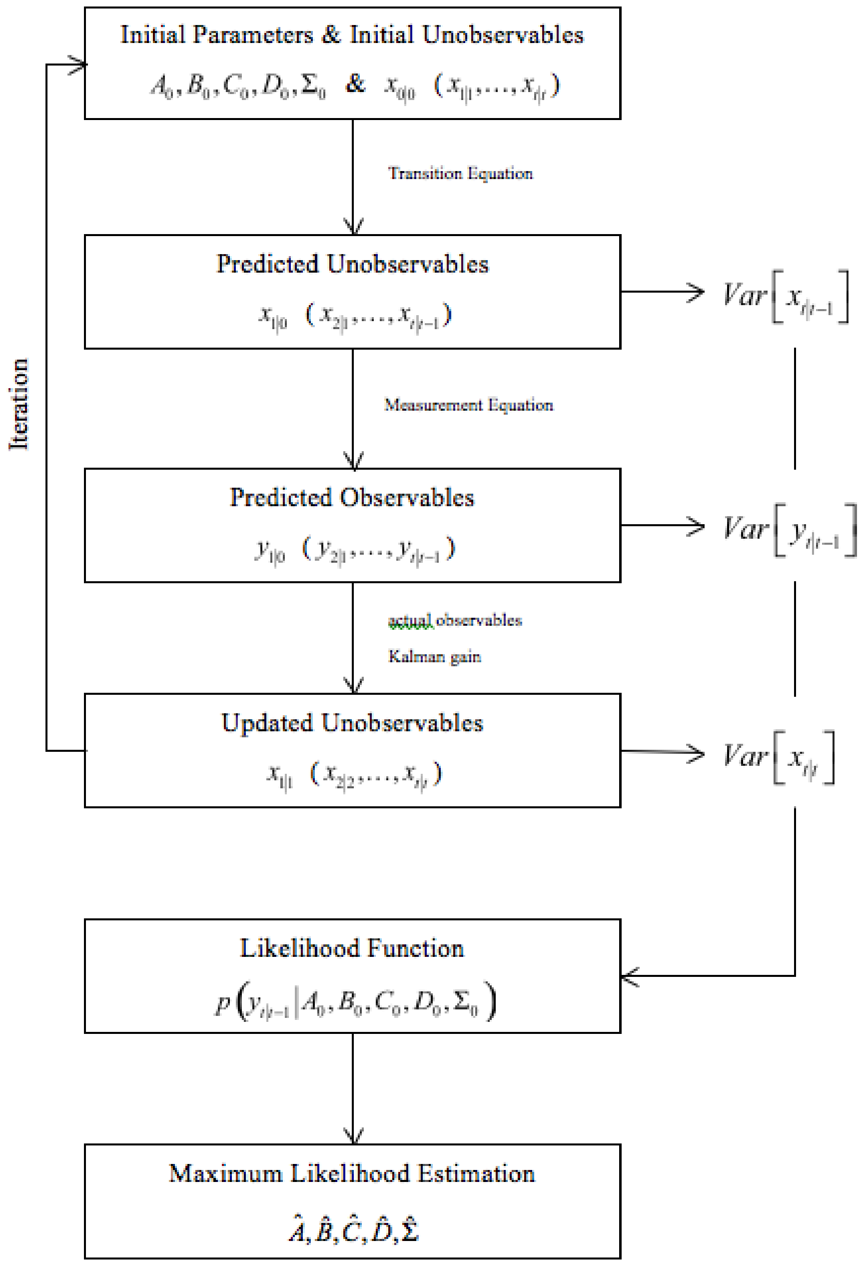
Step 2: Estimate the likelihood function.

The prediction stage starts with some initial values of parameters $A_0, B_0, C_0, D_0, \Sigma_0$ and unobservables $x_{0|0}$. The predicted unobservables $x_{1|0}$ are then obtained through a transition equation. The observables $y_{1|0}$ are then predicted through a measurement equation. The updating Stage obtains the updated unobservables $x_{1|1}$ based on two sources of information, which are: firstly, the prediction error between the predicted observables (simulated) $y_{1|0}$ and actual observables y_1, and secondly, the Kalman gain which minimises $var\left[x_{1|1}\right]$. Iterate over the sample period $t \in \left[1, T\right)$ to obtain the corresponding likelihood function components for each $y_{t|t-1}$, based on the variances of $x_{t|t-1}$, $y_{t|t-1}$, and $x_{t|t}$.

Step 3: Maximum likelihood estimation.

The initial values $A_0, B_0, C_0, D_0, \Sigma_0$ are just one special point in the parameter space. It will then numerically search for the parameters $\hat{A}, \hat{B}, \hat{C}, \hat{D}, \hat{\Sigma}$ which maximise the likelihood function obtained in Step 2. After setting the prior probability distribution and estimating the likelihood function, the next step is to do posterior simulation, which generates random draws $\theta^{(s)}$. Figure 4.1 below describes the procedure of Kalman Filter for estimation.

Figure 4.1 The Procedure of Kalman Filter Estimation



If the posterior $p(\theta|y)$ has a common form like a Normal or Chi Squared distribution, which means the analytical solution exists, then a Monte Carlo Integration can be directly implemented to estimate the mean and variance of the posterior density as well as the Numerical Standard Error. If, however, the posterior $p(\theta|y)$ does not have a common form, then random draws from the posterior cannot be directly achieved. In this case, it is advisable to either use independent draws from a certain source density that well approximates the posterior density or to use dependent draws based on a Markov chain. The independent posterior simulation includes Acceptance Sampling and Importance Sampling, while the dependent posterior simulation includes Markov Chain Monte Carlo (MCMC) Algorithm such as Gibbs Sampler and Metropolis-Hastings (MH) Algorithm.

In this chapter, a Metropolis-Hastings (MH) Algorithm is used to do a posterior simulation. MH is an MCMC algorithm because the current draw always depends on the previous draw. These draws are made to mimic draws from the posterior by taking many draws from regions of the parameter space where posterior probability is higher and fewer draws from regions where the posterior probability is low. The basic idea is to get a candidate probability density function, which usually appears either as a normal or chi-square distribution. The candidate distribution can indicate if the acceptance rate to decide the draws from the candidate distribution can be used or not, sometimes using j-scale to measure the acceptance rate. The best acceptance rate should be in the 20% to 40% integral.

Besides using the Bayes' rule to do parameters estimation, one advantage of the Bayesian approach used in this chapter is that it provides a framework for comparing and choosing between fundamentally misspecified models. This comparison can be done on the basis of the marginal likelihood of the model. The marginal likelihood of a model *A* is defined as:

$$M = \int_{\theta} p(\theta | A) p(y_t | \theta, A) d\theta \tag{4.2}$$

where $p(\theta | A)$ is the prior density for model *A* and $p(y_t | \theta, A)$ is the probability density function or the likelihood function of the observable data series, y_t , conditional on model *A* and parameter vector θ. By integrating out the parameters of the model, the marginal likelihood of a model gives an indication of the overall likelihood of the model given the data.

Here the event *A* is now the model *M* and the event *B* can still be treated as observable data y_t . Since $p(y)$ is hard to calculate directly, the second way of comparing different models is to use a *Posterior Odds (PO)* ratio:

$$PO_{ij} = \frac{p(M_i | y)}{p(M_j | y)} = \frac{p(y | M_i) p(M_i)}{p(y | M_j) p(M_j)} \tag{4.3}$$

In particular, if the prior model probabilities for different models are set equal, then the *PO* ratio becomes the *Bays Factor*:

$$BF_{ij} = \frac{p(y | M_i)}{p(y | M_j)} \tag{4.4}$$

The marginal likelihood of a model reflects the prediction performance of a model. Similarly, the Bayes factor compares the models’ ability to predict out of sample.

4.4 Data and Priors

In order to estimate the parameters of the DSGE model with Bayesian estimation techniques, seven key macro-economic variables in France over period 1978Q1 to 2010Q4 are used, which are: real GDP, real consumption, real investment, GDP deflator, real wages, hours worked, and the nominal interest rate. Capital stock, the value of capital and the rental rate of capital are assumed to be unobserved. Since there are two shocks in the wage equation and monetary policy equation, in order to identify the shocks, the labour supply and inflation targeting shocks are ignored in this thesis and the number of observables is considered to be equal to the number of shocks.

In Bayesian estimation framework the first prior density for the model parameters needs to be specified. It is then combined with the likelihood function of the observed data series, which is calculated with the Kalman filter as in Sargent (1989) to obtain the posterior distribution of parameters.

Some of parameters were kept fixed before the exercise, which can be seen as a very strict prior. The discount factor β is calibrated to be 0.99, which implies an annual steady state real interest rate of 4%. The depreciation rate δ is set equal to 0.025 per quarter, which implies an annual depreciation on capital equal to 10%. The parameter α set equal to 0.30, which roughly implies a steady state share of labour income in total output of 70%. The share of steady-state consumption in total output is assumed to be 0.6, while the share of steady-state investment is assumed to be 0.22. This also implies a steady-state capital output ratio of about 8.8. In addition, the parameter capturing the markup in wage setting is fixed and is set to 0.5. The share of each sector in GTE and the survival functions in GC is calibrated according to the micro data. The data details can be found in Baudry, le Bihan et al. (2004), Fougre, le Bihan et al. (2007), Dixon and le Bihan et al. (2010). Note that the parameters to measure heterogeneity in GTE and GC price setting as well as parameters to measure homogeneous price stickiness are treated as fixed parameters.

All of the variances of shocks are assumed to follow an inverted gamma distribution with a degree of freedom equal to 2, which is the same as in SW (2003) who explained that this distribution guarantees a positive variance with a rather large domain. The distribution of the autoregressive parameters in measuring shocks is assumed to follow a beta distribution with mean 0.85 and standard error 0.1. The mean of the intertemporal elasticity of substitution is set equal to one, which is consistent with log preferences and the findings of Casares (2001) for the Euro area. The elasticity of the capital utilisation cost function has a mean of 0.2, and includes in its domain the value of 0.1 which is suggested by King and Rebelo(2000). For some of the other parameters (such as the elasticity of the cost of adjusting investment or the share of fixed costs in total production) the values are set close to those estimated by CEE (2001) for the U.S. A wide range of calibrations has been used for the inverse elasticity of labour supply. The starting point value of the inverse of elasticity of labour supply was chosen as 2, which falls in the relatively low elasticities that are typically estimated in the micro labour literature and larger elasticities typically in the DSGE model. Finally, the prior on the coefficients in the monetary policy reaction function are quite standard. A relatively high long-term coefficients on inflation helps to guarantee a unique solution path when solving the model. The lagged interest rate prior follows a normal distribution of mean 0.8 with a standard error 0.1, and the output reaction function coefficient is set around a value that correspond with the Taylor coefficient of 0.5.

4.5 Results

The models are solved and estimated with the Dynare 4.2.1. The method to do a posterior simulation is a Metropolis-Hastings algorithm, which generates 20,000 draws with acceptance rate between 20% and 40% for each model.

4.5.1 Results Summary of Different Price Setting Models

The parameter estimates are quite different from the different price setting models. Table 4.1 summarises the means of the posterior distributions of the parameters obtained by the Metropolis-Hastings algorithm in different price setting models. Overall, most parameters are estimated to be significantly different from zero. Most parameters are very similar to the results estimated in SW (2003). One difference between this study and SW (2003) are the data set, which in this thesis it only focuses on the French economy, besides that, the parameter to measure the survival rate of Calvo price contract is fixed as the average frequency of price changes in GC in order to make the model comparison in the same price stickiness dimension.

Table 4.1Summary Estimation Results of Different Price Setting Models

Parameter	***Prior Dist***	***Prior Mean***	***IC***	***GC***	***GTE***	***Calvo***	***Taylor***
γ_w	Beta	0.75	0.4904	0.8303	0.8737	0.9554	0.2131
h	Beta	0.70	0.9474	0.9474	0.9490	0.9482	0.9475
φ	Normal	4.00	7.3518	5.0725	7.4526	5.7434	5.1837
ψ	Normal	0.20	0.1384	0.1127	0.2008	0.1746	0.1014
$r_{\Delta\pi}$	Normal	0.30	0.3850	0.2268	0.2921	0.1781	0.1290
$r_{\Delta y}$	Normal	0.0625	0.2129	0.1139	0.0715	0.1508	0.1754
ρ	Beta	0.80	0.9295	0.9287	0.9160	0.9342	0.9307
r_π	Normal	1.70	1.9085	1.6525	1.7356	1.7921	1.4705
r_y	Normal	0.125	0.1479	0.1115	0.1722	0.1014	0.1038
σ_c	Normal	1.00	2.5946	2.6438	2.4460	2.4717	2.2265
σ_l	Normal	2.00	0.5623	1.2401	0.6631	0.5750	0.5480
ϕ	Normal	1.45	1.2582	1.7634	1.8979	1.7826	1.6953
ξ_w	Beta	0.75	0.7223	0.7243	0.6638	0.5993	0.5780

Table 4.1 shows that different price mechanism DSGE models have different posterior distribution of the structural coefficients. Focusing on those parameters governing wage setting equations, the survival rate of Calvo wage setting equation ξ_w is similar between IC and GC price setting models, which is around 0.72; therefore, this implies that the average duration of wage contracts is around one and half years. In the GTE, simple Calvo, and simple 4-period Taylor price setting models the survival rate to measuring Calvo wage setting behaviour is less rigid than in IC and GC price setting models. The indexation parameter associated with Calvo wage setting significantly differs among these pricing models: the IC (0.4904) and simple 4-period Taylor (0.2131) price setting models yield the lower value of indexation parameter in wage setting equation than other models, which indicates the less forward-looking component in the wage setting equation.

All of the models imply a very high degree of habit formation, which is nearly close to one. The estimate of habit persistence parameter is much higher than that in SW (2003) (0.573), which indicates that the consumption smoothing process is stronger in the French economy. The very high degree of habit persistence through these five different price setting models is also consistent with the estimates presented in Laforte (2007) for studying U.S. economy which is found to be particularly useful in matching the high persistence in the U.S. output volatility. Thus, this high value of this estimates h also demonstrate that this consumption rigidity is another important feature to generate output persistence which is also discussed in Chapter 2. In addition, the intertemporal elasticity of substitution $1/\sigma_c$ is less than one in all price setting models, while the range of the estimates obtained from different price setting models is between 0.38 and 0.45. From the Euler equation of consumption it can be seen that the estimates of $1/\sigma_c$ and h imply that changing the short term interest rate has very little impact on consumption. Focusing on the parameter governing the investment adjustment cost function φ in GTE and IC models it can be seen that there is 0.15% increase in investment following a 1% increase in the current price of installed capital. While in GC, simple Calvo, and Taylor price setting models, the extent of increase in investment following a 1% increase in current price of installed capital is relative higher, which implies a more investment persistence. The estimates of inverse elasticity of capital utilisation ψ differs among the five various price setting models, with value from 0.1014 to 0.2008. GTE and Calvo exhibit higher value than SW(2003) (0.169) which implies a less capital utilisation cost and thus less persistence in capital accumulation.

Turning to the parameters in monetary policy function, the estimates in these different price setting models are in line with those proposed by Taylor (1993). The estimates imply that there is a substantial degree of interest rate smoothing, which is approximately around 0.92 in all models. In addition, the long run response of interest rate to inflation was greater than 1, which can also be shown in all of these models, and IC shows the strongest effect compared with other models. The significant positive short-term reaction to current change in inflation and the output gap are also to be found in all models, IC still yields the strongest response.

Focusing on the parameter to measure elasticity of labour supply it can be seen that the estimate of σ_l differs substantially among these different price setting models. This parameter's value is around 0.55 in IC, GTE, Calvo, and Taylor, which implies that the labour supply is highly elastic to the change in the wage rate. This estimate is quite different to the one estimated in SW (2003) with value 2.4, although SW (2003) pointed out that this estimate did not prove to be very robust across specifications. In the GC price setting model σ_l equals 1.2401, which demonstrates the inelastic of labour supply to the changes of real wage compared with other models.

4.5.2 Model Comparison

Table 4.2 presents the statistical results of comparing different price setting models. The first row reports the log marginal likelihood of each model,[12] which reflects the model's predictive performance. From the marginal probability criterion it can be seen that the GC model has the largest value compared with the others, which implies

[12] A modified harmonic mean is used to measure marginal probability since it is not sensitive to the step size for the MH algorithm.

that GC model does the best job in predicting the seven variables over the period 1978Q1 to 2010Q4 in France. In addition, the result shows that the data favours the conventional Calvo price model to Calvo with partial indexation model, which is in line with the results shown in Laforte (2007) who find that an indexation scheme cannot significantly improve the model's performance.

Table 4.2 Statistical Measures to Compare Models

	IC	***GC***	***GTE***	***Calvo***	***Taylor***
Log Marginal Likelihood	-1312.12	-1124.39	-1252.37	-1242.79	-1321.01
Bayes Factors relative to the GC	$e^{186.73}$	e^{0}	$e^{127.98}$	$e^{118.40}$	$e^{195.62}$

The use of Bayes Factors to compare models was first suggested by Jeffreys (1965), who suggests the following rule of thumb for interpreting Bayes factors:

Table 4.3 Jeffrey's Guidelines for Interpreting Bayes Factors

Bayes Factors	
1 to 3.2	Not worth more than a bare mention
3.2 to 10	Substantial
10 to 100	Strong
>100	Decisive

It can be seen from Jeffrey's guidelines as illustrated in Table 4.3 that the data indicates the 'decisive' evidence for the GC price setting model. The key factor behind this strong result comes from the heterogeneous price stickiness. The hazard function in GC price setting is no longer a constant and dependent according to the finite price duration. Although in GC price setting the contract duration is no longer infinite as in the Calvo contract setup, GC is found to be more forward looking when compared with the other heterogeneity price setting behaviours as GTE. The uncertainty essence in a Calvo type contract makes the GC much closer to mimicking the seven main macro variables in the French economy from 1978Q1 to 2010Q4.

The results also indicate that a partial lagged indexation scheme is a poor expedient to explain the real data. From this point of view, the indexation scheme is neither theoretically supported nor empirically proved. Surprisingly, the introduction of heterogeneity to the Taylor model cannot improve the model's performance. The Bayes factor between simple Calvo and the GTE is $e^{9.58}$, which means that compared with GTE the data favours simple Calvo strongly.

The reason why heterogeneous GTE price setting model cannot improve the model's performance is due to the lack of enough sectors in the model. In this thesis, since the availability of the micro data evidence is up to 24 months, the multi-sector economy only has price-spells of up to 8 periods, with 8 period contracts absorbing the remaining weight from the longer contract. These 8 sector settings cannot capture the long tail of Calvo type mechanism, which has infinite price spells. This result is in line with the findings in Dixon and Kara (2011) who found that when truncating the price spells to shorter periods, its performance is worse than those with longer price spells included.

4.5.3 Other issues of the Robustness Check

Different priors and observables are investigated in order to check the robustness of the Bayesian approach to do the model estimation and comparison. The results show that the relative ranking of these five different price setting models is not changed.

4.5.3.1 The choice of different number of observables

Chapter 3 uses the auxiliary model VAR(1) in the indirect inference testing procedure which includes five main macro variables (i.e. interest rate, investment, consumption, output and inflation) to measure the model's overall capacity to fit the data. All of the models are rejected at even a 99% confidence interval. Consequently, there is no need to include more variables into consideration since the inclusion of more variables only makes the threshold stricter to achieve (Le, Meenagh et al. 2008). Although the essence of Bayesian estimation is to use as much information as possible to find the set of parameters that can maximise the marginal likelihood, in order to put the estimation and testing in the same criterion in this section the observables are reduced from seven to five in which the real wage and labour are excluded. The estimates of the structural parameters change to some extent, and then Bayes Factors are still used to compare the models.

Table 4.4 summarises the parameter estimates based on the different price setting models by using five observables. In this case the parameters are different from the estimates with seven observables, especially the parameters that govern labour and wages. The elasticity of labour supply in all models is quite similar to the estimates in SW (2003), which is around 0.4, indicating the inelastic of labour supply to real wages. Turning to the parameters governing wage stickiness, the Calvo wage parameter is much stickier than that with seven observables. All in all, the estimates changes considerably when labour and real wages are excluded, especially in the parameters governing wages and labour supply.

Table 4.4 Summary Estimation Results of Different Price Setting Models with Five Observables

Parameter	***Prior Dist***	***Prior Mean***	***IC***	***GC***	***GTE***	***Calvo***	***Taylor***
γ_w	Beta	0.75	0.6156	0.5783	0.5755	0.7982	0.2815
h	Beta	0.70	0.8808	0.8808	0.9094	0.8885	0.8932
φ	Normal	4.00	4.6861	4.3854	4.0767	2.7272	3.8070
ψ	Normal	0.20	0.1648	0.2097	0.1976	0.1714	0.1928
$r_{\Delta\pi}$	Normal	0.30	0.1471	0.2384	0.1099	0.1891	0.1213
$r_{\Delta y}$	Normal	0.0625	0.2018	0.1630	0.2025	0.1770	0.2454
ρ	Beta	0.80	0.9336	0.9292	0.9381	0.9297	0.9549
r_π	Normal	1.70	1.5985	1.7383	1.6403	1.6462	1.6778
r_y	Normal	0.125	0.1666	0.1264	0.1692	0.1483	0.1816
σ_c	Normal	1.00	1.5277	1.7460	1.4948	1.6287	1.5797
σ_l	Normal	2.00	2.8523	2.8572	2.4533	2.3466	2.1137
ϕ	Normal	1.45	1.4902	1.4635	1.6617	1.4281	1.6031
ξ_w	Beta	0.75	0.8164	0.7782	0.8410	0.8292	0.8527

Although the number of observables is changed, the ranking of the model is still unchanged. Table 4.5 below shows the marginal likelihood based on the different price setting models. Once again, the results strongly favour GC.

Table 4.5 Statistical Measures to Compare Models with Five Observables

	IC	***GC***	***GTE***	***Calvo***	***Taylor***
Log Marginal Likelihood	-489.72	-475.52	-487.33	-479.52	-619.92
Bayes Factors relative to the GC	$e^{14.2}$	e^{0}	$e^{11.81}$	e^{4}	$e^{144.4}$

Turning to those variables which are the key interest of monetary policy analysis, Table 4.6 below reports the estimation results of different price setting models with three observables (i.e. inflation, output and interest rate):

Table 4.6 Summary Estimation Results of Different Price Setting Models with Three Observables

Parameter	*Prior Dist*	*Prior Mean*	*IC*	*GC*	*GTE*	*Calvo*	*Taylor*
γ_w	Beta	0.75	0.2818	0.5376	0.5877	0.3578	0.3474
h	Beta	0.70	0.8713	0.8717	0.9061	0.8898	0.9164
φ	Normal	4.00	3.8026	3.1519	4.0513	3.7991	5.2588
ψ	Normal	0.20	0.2212	0.2236	0.1993	0.2001	0.2120
$r_{\Delta\pi}$	Normal	0.30	0.1899	0.2293	0.1411	0.1913	0.1561
$r_{\Delta y}$	Normal	0.0625	0.2088	0.1920	0.1977	0.1860	0.1688
ρ	Beta	0.80	0.9576	0.9555	0.9584	0.9605	0.9470
r_{π}	Normal	1.70	1.6551	1.7178	1.6644	1.6598	1.5994
r_y	Normal	0.125	0.1682	0.1725	0.1811	0.2000	0.1661
σ_c	Normal	1.00	1.1466	1.2469	1.0476	1.2106	1.1958
σ_l	Normal	2.00	2.3789	2.5978	2.4509	2.4548	1.7748
ϕ	Normal	1.45	1.5925	1.6012	1.6826	1.5521	1.3200
ξ_w	Beta	0.75	0.8488	0.8446	0.8780	0.8606	0.7777

Table 4.6 summarises the parameter estimates based on the different price setting models by using three observables. The results do not differ considerably when these results are compared with those estimates which use five observables with consumption and investment are excluded. The primary difference is the indexation parameter in wage setting equation: when only considering the three main macro variables, all of the models are more forward looking in wage setting than when five main macro variables take into consideration.

Although the number of observables is changed from seven to five, five to three, the ranking of the model is still unchanged. Table 4.7 below shows the marginal likelihood based on the different price setting models. Once again, the results strongly favour GC.

Table 4.7 Statistical Measures to Compare Models with Three Observables

	IC	***GC***	***GTE***	***Calvo***	***Taylor***
Log Marginal Likelihood	-176.956	-137.458	-172.652	-163.763	-308.747
Bayes Factors relative to the GC	$e^{39.498}$	e^{0}	$e^{35.194}$	$e^{26.305}$	$e^{171.289}$

4.5.3.2 The choice of different priors

Although the estimates of structural different price setting models using Bayesian technique are largely in line with SW (2003), there is one significant difference exists in the value of elasticity of labour supply which is not proven as a robust value. To check robustness the prior mean of this parameter changes from 2 to 0.5, this is also in line with the range to be found in the labour literature.

Table 4.8 reports the parameter estimates of different price setting models by changing the prior of inverse of elasticity of labour supply from 2 to 0.5 with using seven observables in the measurement equation. This parameter's value changes considerably after changing the prior of inverse of elasticity of labour supply. All of the models exhibit very high elastic of labour supply to the real wage. When compared with the benchmark results (see in Table 4.1) all of the models yield a more backward looking behaviour in the wage setting equation.

Table 4.8 Summary Estimation Results of Different Price Setting Models with Different Priors

Parameter	***Prior Dist***	***Prior Mean***	***IC***	***GC***	***GTE***	***Calvo***	***Taylor***
γ_w	Beta	0.75	0.9006	0.9007	0.8060	0.8020	0.5294
h	Beta	0.70	0.9486	0.9473	0.9488	0.9483	0.9459
φ	Normal	4.00	7.7481	3.9390	4.2715	4.0028	5.9620
ψ	Normal	0.20	0.2140	0.2284	0.1014	0.3011	0.2232
$r_{\Delta\pi}$	Normal	0.30	0.2996	0.2757	0.2348	0.2498	0.1756
$r_{\Delta y}$	Normal	0.0625	0.1673	0.1329	0.0646	0.1075	0.1182
ρ	Beta	0.80	0.9310	0.9290	0.9053	0.9252	0.9362
r_π	Normal	1.70	1.7456	1.7306	1.5406	1.5317	1.6130
r_y	Normal	0.125	0.1456	0.0894	0.1086	0.0774	0.1676
σ_c	Normal	1.00	2.6362	2.5278	2.2715	2.7422	2.0695
σ_l	Normal	0.50	0.2996	0.3500	0.3164	0.2911	0.3676
ϕ	Normal	1.45	1.4977	1.6347	1.9524	1.9487	1.7450
ξ_w	Beta	0.75	0.6697	0.7906	0.6709	0.6910	0.6375

Table 4.9 shows the Bayes Factor of different price setting models with different priors, the results again favour GC strongly. Changing the prior setting of the inverse of elasticity of labour supply from 2 to 0.5 does not change the ranking of these price setting models.

Table 4.9 Statistical Measures to Compare Models with Different Priors

	IC	***GC***	***GTE***	***Calvo***	***Taylor***
Log Marginal Likelihood	-1259.76	-1107.92	-1242.15	-1232.60	-1311.06
Bayes Factors relative to the GC	$e^{151.84}$	e^{0}	$e^{134.23}$	$e^{124.68}$	$e^{203.14}$

4.6 Conclusion

In this chapter the Bayesian estimation method is applied to estimate the different price setting models of the French economy. Bayesian estimation method combines the likelihood function of the data with prior distributions for the model parameters to estimate the mode of the posterior function by maximising the log posterior density function. This posterior distribution is get from Monte-Carlo Markov-Chain methods (Metropolis-Hastings algorithm). There are three main advantages of a Bayesian estimation method: the first is that the use of prior distribution can allow the previous microeconometric and macroeconometric studies to be taken into consideration, which provides a way to link the previously calibration-based literature; the second is that this method can still provide valuable stable results when the sample of data is relatively small; in addition, a Bayesian approach can provide a way to evaluate fundamentally misspecified models, which can be done with a marginal likelihood of the model or Bayes Factors. The marginal likelihood of a model is directly related to the predictive density function. The predictive performance is the natural criterion for validating models for forecasting and policy analysis.

The results strongly favour the GC price mechanism above other price settings. The Bayesian model comparison exercise yields a significant marginal likelihood to the GC model over the other pricing schemes. From this point of view, the introduction of heterogeneity in price stickiness can improve the model's ability to predict over that of the more conventional homogenous price mechanisms. In addition, the other important finding is that adding an indexation scheme to the Calvo price model cannot improve the model's fitness to the data. In addition, another important parameter, the elasticity of labour supply, is not pinned down very precisely by the data. In future research, it would be interesting to incorporate the heterogeneity of wage stickiness into the model and assess the sole effect of nominal and real rigidity. In addition, in this thesis the sectoral price stickiness to measure the heterogeneity in price equation is fixed from the micro price evidence of the French economy. In future research, the microeconometric evidence of price and wage data can be used as a prior and the parameters to governing the sectoral price and wage stickiness can be estimated by using Bayesian estimation method.

Appendix 2

Table 4.10 Parameter Estimates of IC price settings

	Prior distribution			*Calvo with Indexation*		
				Estimated Maximum Posterior/MH posterior		
	Type	***Mean***	***s.e.***	***Mode***	***MH Mode***	***Mean***
γ_w	Beta	0.75	0.15	0.4866	0.4900	0.4904
h	Beta	0.70	0.10	0.9500	0.9480	0.9474
φ	Normal	4.00	1.5	7.4210	7.6319	7.3518
ψ	Normal	0.20	0.075	0.1406	0.1491	0.1384
$r_{\Delta\pi}$	Normal	0.30	0.10	0.4159	0.3890	0.3850
$r_{\Delta y}$	Normal	0.0625	0.05	0.1975	0.2217	0.2129
ρ	Beta	0.80	0.10	0.9328	0.9264	0.9295
r_π	Normal	1.70	0.10	1.9300	1.9049	1.9085
r_y	Normal	0.125	0.05	0.1386	0.1542	0.1479
σ_c	Normal	1.0	0.375	2.5349	2.6822	2.5946
σ_l	Normal	2.0	0.75	0.5000	0.5382	0.5623
ϕ	Normal	1.45	0.25	1.2856	1.2787	1.2582
ξ_w	Beta	0.75	0.05	0.7180	0.7342	0.7223
$\rho\left(\varepsilon_t^a\right)$	Beta	0.85	0.10	0.9992	0.9995	0.9977
$\rho\left(\varepsilon_t^b\right)$	Beta	0.85	0.10	0.4720	0.4625	0.4715
$\rho\left(\varepsilon_t^G\right)$	Beta	0.85	0.10	0.9729	0.9719	0.9657
$\rho\left(\varepsilon_t^I\right)$	Beta	0.85	0.10	0.3180	0.3712	0.3591
$\rho\left(\eta_t^Q\right)$	Beta	0.85	0.10	0.9949	0.9910	0.9922
$\sigma\left(\varepsilon_t^a\right)$	Inv gamma	0.40	2*	0.5920	0.5597	0.5816
$\sigma\left(\varepsilon_t^b\right)$	Inv gamma	0.20	2*	0.2351	0.2619	0.2480
$\sigma\left(\varepsilon_t^G\right)$	Inv gamma	0.30	2*	0.3480	0.3479	0.3682
$\sigma\left(\varepsilon_t^I\right)$	Inv gamma	0.10	2*	0.5495	0.5099	0.5273
$\sigma\left(\eta_t^Q\right)$	Inv gamma	0.40	2*	0.1091	0.1210	0.1256
$\sigma\left(\eta_t^R\right)$	Inv gamma	0.25	2*	0.2815	0.2829	0.2820
$\sigma\left(\eta_t^w\right)$	Inv gamma	0.10	2*	4.6181	4.4268	4.5261

Figure 4.2 Estimated Parameters Distribution of IC price setting

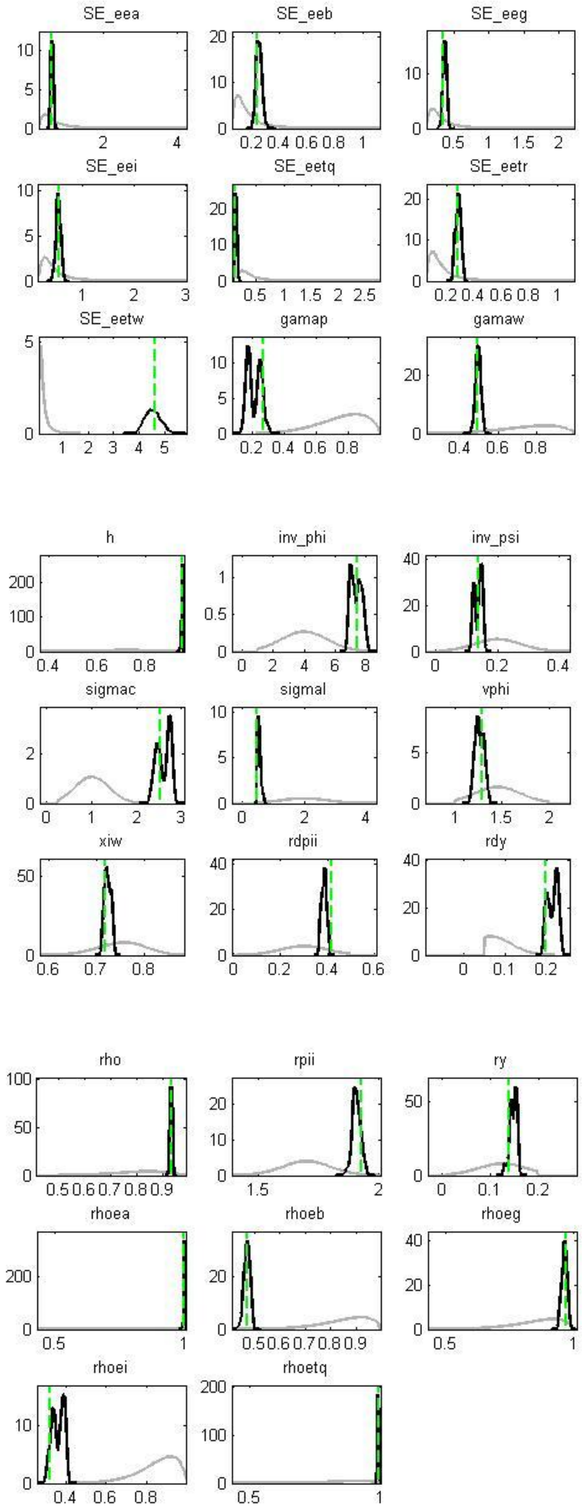


Table 4.11 Parameter Estimates of GC price settings

	prior distribution			*Generalised Calvo* *Estimated Maximum Posterior/MH posterior*		
	Type	***Mean***	***s.e.***	***Mode***	***MH Mode***	***Mean***
γ_w	Beta	0.75	0.15	0.8498	0.9381	0.8303
h	Beta	0.70	0.10	0.9500	0.9495	0.9474
φ	Normal	4.00	1.5	4.8899	5.8982	5.0725
ψ	Normal	0.20	0.075	0.1447	0.1405	0.1127
$r_{\Delta\pi}$	Normal	0.30	0.10	0.2251	0.2160	0.2268
$r_{\Delta y}$	Normal	0.0625	0.05	0.1237	0.1324	0.1139
ρ	Beta	0.80	0.10	0.9297	0.9271	0.9287
r_π	Normal	1.70	0.10	1.6724	1.7192	1.6525
r_y	Normal	0.125	0.05	0.1102	0.0986	0.1115
σ_c	Normal	1.0	0.375	2.6890	2.6693	2.6438
σ_l	Normal	2.0	0.75	1.1799	1.2941	1.2401
ϕ	Normal	1.45	0.25	1.8024	1.8137	1.7634
ξ_w	Beta	0.75	0.05	0.7320	0.7131	0.7243
$\rho\left(\varepsilon_t^a\right)$	Beta	0.85	0.10	0.9114	0.9176	0.9136
$\rho\left(\varepsilon_t^b\right)$	Beta	0.85	0.10	0.4255	0.4127	0.4423
$\rho\left(\varepsilon_t^G\right)$	Beta	0.85	0.10	0.9770	0.9763	0.9754
$\rho\left(\varepsilon_t^I\right)$	Beta	0.85	0.10	0.7960	0.7542	0.8011
$\rho\left(\eta_t^Q\right)$	Beta	0.85	0.10	0.9852	0.9876	0.9867
$\sigma\left(\varepsilon_t^a\right)$	Inv gamma	0.40	2*	0.7481	0.7284	0.7518
$\sigma\left(\varepsilon_t^b\right)$	Inv gamma	0.20	2*	0.2236	0.2319	0.2227
$\sigma\left(\varepsilon_t^G\right)$	Inv gamma	0.30	2*	0.3488	0.3445	0.3535
$\sigma\left(\varepsilon_t^I\right)$	Inv gamma	0.10	2*	0.2763	0.2938	0.2858
$\sigma\left(\eta_t^Q\right)$	Inv gamma	0.40	2*	0.1466	0.1473	0.1409
$\sigma\left(\eta_t^R\right)$	Inv gamma	0.25	2*	0.2405	0.2608	0.2427
$\sigma\left(\eta_t^w\right)$	Inv gamma	0.10	2*	1.7545	1.7543	1.8085

Figure 4.3 Estimated Parameters Distribution of GC price setting

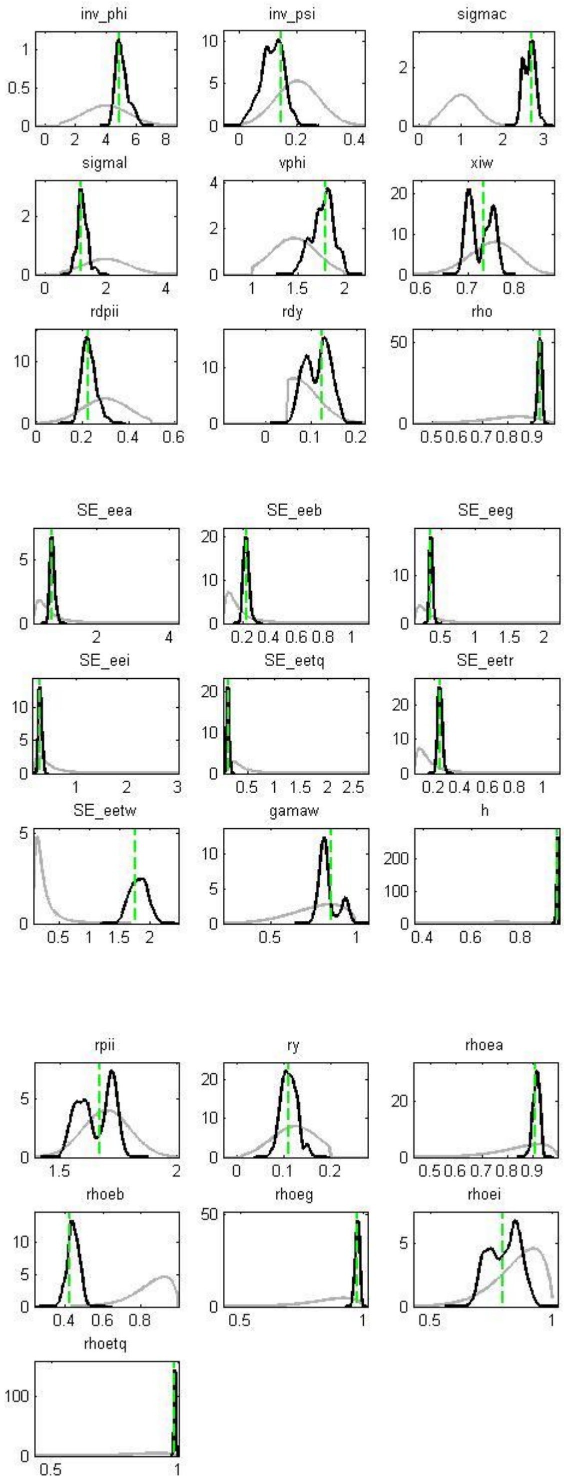


Table 4.12 Parameter Estimates of GTE price settings

	prior distribution			*Generalised Taylor Economy*		
				Estimated Maximum Posterior/MH posterior		
	Type	***Mean***	***s.e.***	***Mode***	***MH Mode***	***Mean***
γ_w	Beta	0.75	0.15	0.8853	0.8639	0.8737
h	Beta	0.70	0.10	0.9500	0.9494	0.9490
φ	Normal	4.00	1.5	7.5100	7.0656	7.4526
ψ	Normal	0.20	0.075	0.2023	0.1846	0.2008
$r_{\Delta\pi}$	Normal	0.30	0.10	0.2623	0.2703	0.2921
$r_{\Delta y}$	Normal	0.0625	0.05	0.0559	0.0909	0.0715
ρ	Beta	0.80	0.10	0.9150	0.9051	0.9160
r_π	Normal	1.70	0.10	1.7123	1.7428	1.7356
r_y	Normal	0.125	0.05	0.1728	0.1587	0.1722
σ_c	Normal	1.0	0.375	2.2483	2.5144	2.4460
σ_l	Normal	2.0	0.75	0.5001	0.5917	0.6631
ϕ	Normal	1.45	0.25	1.9852	1.8833	1.8979
ξ_w	Beta	0.75	0.05	0.6767	0.6957	0.6638
$\rho\left(\varepsilon_t^a\right)$	Beta	0.85	0.10	0.9613	0.9629	0.9626
$\rho\left(\varepsilon_t^b\right)$	Beta	0.85	0.10	0.4657	0.4987	0.5093
$\rho\left(\varepsilon_t^G\right)$	Beta	0.85	0.10	0.9760	0.9834	0.9767
$\rho\left(\varepsilon_t^I\right)$	Beta	0.85	0.10	0.4138	0.4555	0.4602
$\rho\left(\eta_t^Q\right)$	Beta	0.85	0.10	0.9911	0.9939	0.9922
$\sigma\left(\varepsilon_t^a\right)$	Inv gamma	0.40	2*	0.6196	0.6320	0.6297
$\sigma\left(\varepsilon_t^b\right)$	Inv gamma	0.20	2*	0.3103	0.2895	0.2885
$\sigma\left(\varepsilon_t^G\right)$	Inv gamma	0.30	2*	0.3501	0.3451	0.3499
$\sigma\left(\varepsilon_t^I\right)$	Inv gamma	0.10	2*	0.5932	0.5118	0.5593
$\sigma\left(\eta_t^Q\right)$	Inv gamma	0.40	2*	0.7320	0.7346	0.7264
$\sigma\left(\eta_t^R\right)$	Inv gamma	0.25	2*	0.2587	0.2721	0.2635
$\sigma\left(\eta_t^w\right)$	Inv gamma	0.10	2*	4.0940	4.3795	4.2074

Figure 4.4 Estimated Parameters Distribution of GTE price setting

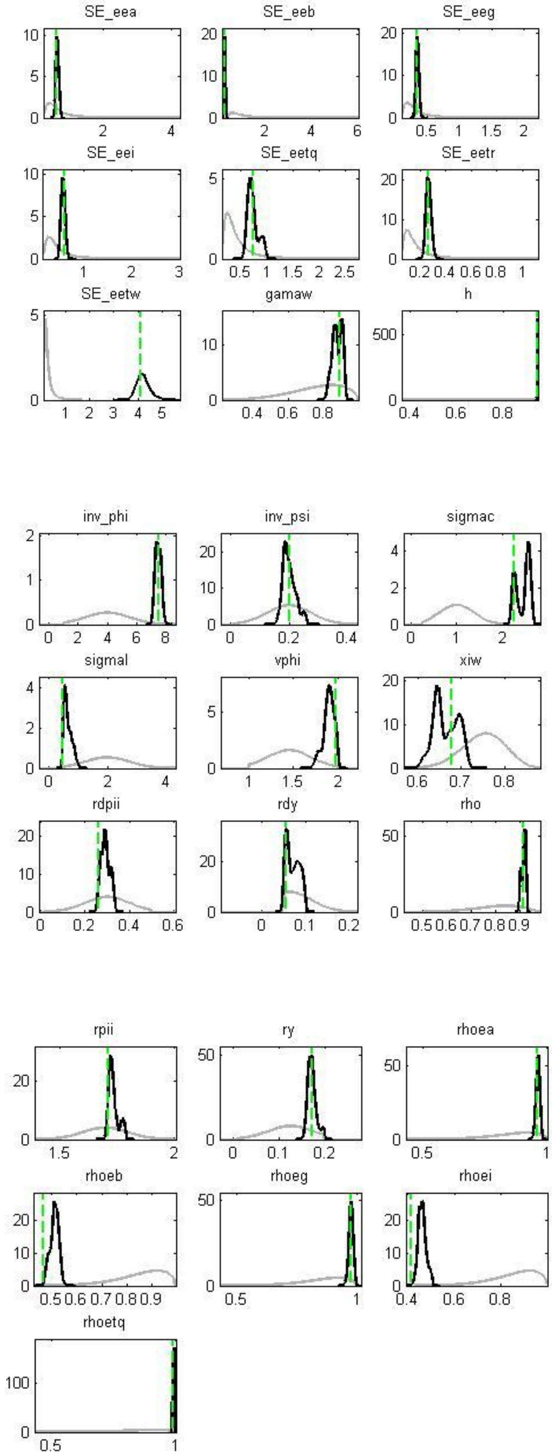


Table 4.13 Parameter Estimates of Calvo price settings

	prior distribution			Calvo		
				Estimated Maximum Posterior/MH		
	Type	*Mean*	*s.e.*	*Mode*	*MH Mode*	*Mean*
γ_w	Beta	0.75	0.15	0.9590	0.9670	0.9554
h	Beta	0.70	0.10	0.9500	0.9496	0.9482
φ	Normal	4.00	1.5	6.1592	5.3715	5.7434
ψ	Normal	0.20	0.075	0.2172	0.1652	0.1746
$r_{\vartriangle\pi}$	Normal	0.30	0.10	0.2254	0.1802	0.1781
$r_{\vartriangle y}$	Normal	0.0625	0.05	0.1669	0.1586	0.1508
ρ	Beta	0.80	0.10	0.9370	0.9341	0.9342
r_π	Normal	1.70	0.10	1.8904	1.7608	1.7921
r_y	Normal	0.125	0.05	0.1106	0.0967	0.1014
σ_c	Normal	1.0	0.375	2.5323	2.5848	2.4717
σ_l	Normal	2.0	0.75	0.5000	0.5390	0.5750
ϕ	Normal	1.45	0.25	1.8917	1.7018	1.7826
ξ_w	Beta	0.75	0.05	0.5836	0.6198	0.5993
$\rho(\varepsilon_t^a)$	Beta	0.85	0.10	0.9432	0.9385	0.9438
$\rho(\varepsilon_t^b)$	Beta	0.85	0.10	0.2399	0.3020	0.3062
$\rho(\varepsilon_t^G)$	Beta	0.85	0.10	0.9746	0.9743	0.9766
$\rho(\varepsilon_t^I)$	Beta	0.85	0.10	0.5499	0.6110	0.6093
$\rho(\eta_t^Q)$	Beta	0.85	0.10	0.9876	0.9848	0.9877
$\sigma(\varepsilon_t^a)$	Inv	0.40	2*	0.6605	0.6564	0.6662
$\sigma(\varepsilon_t^b)$	Inv	0.20	2*	0.3227	0.3213	0.3179
$\sigma(\varepsilon_t^G)$	Inv	0.30	2*	0.3476	0.3638	0.3513
$\sigma(\varepsilon_t^I)$	Inv	0.10	2*	0.3668	0.3659	0.3528
$\sigma(\eta_t^Q)$	Inv	0.40	2*	0.1073	0.1317	0.1216
$\sigma(\eta_t^R)$	Inv	0.25	2*	0.2452	0.2549	0.2404
$\sigma(\eta_t^w)$	Inv	0.10	2*	4.1467	3.8950	4.0365

Figure 4.5 Estimated Parameters Distribution of Calvo price setting

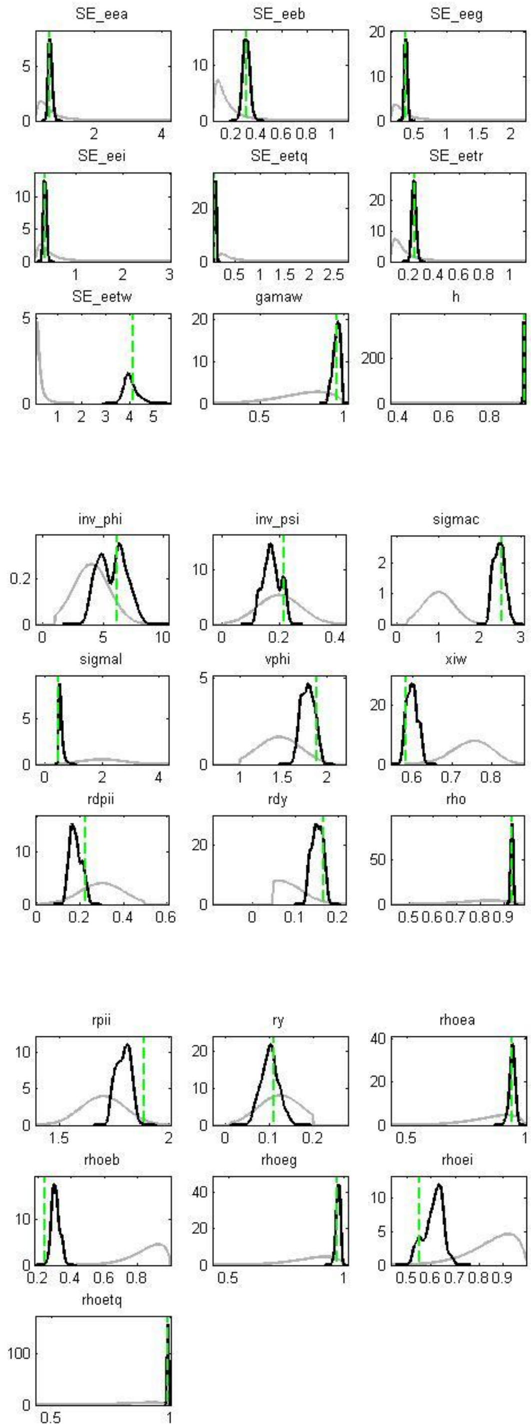
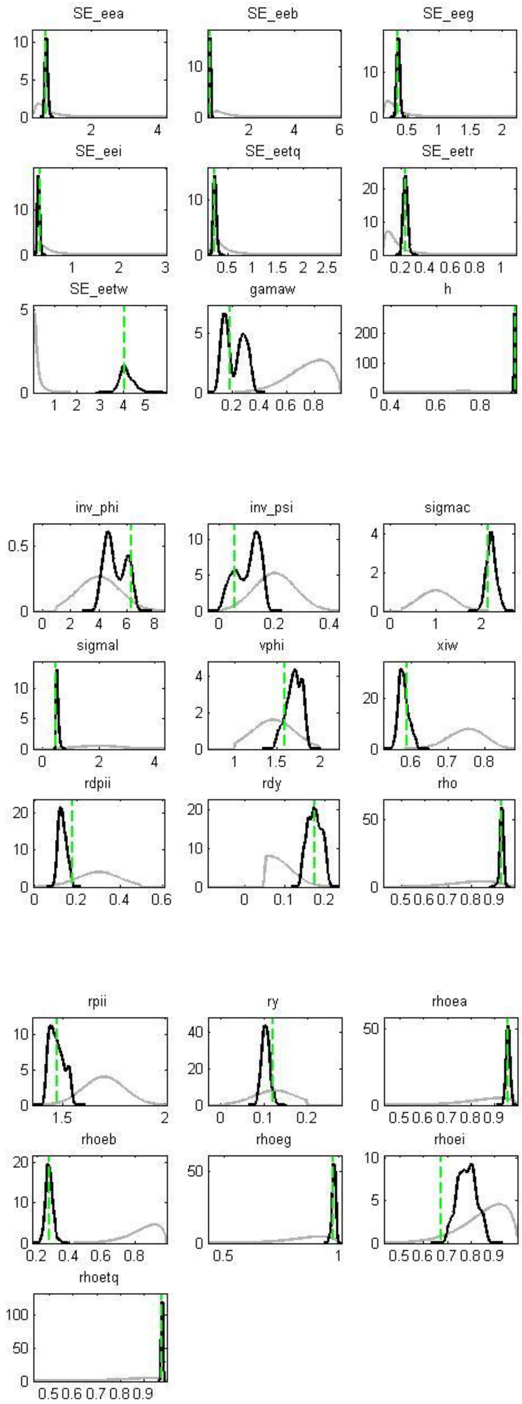


Table 4.14 Parameter Estimates of Taylor price settings

	prior distribution			Taylor		
				Estimated Maximum Posterior/MH posterior		
	Type	*Mean*	*s.e.*	*Mode*	*MH Mode*	*Mean*
γ_w	Beta	0.75	0.15	0.1846	0.3100	0.2131
h	Beta	0.70	0.10	0.9500	0.9487	0.9475
φ	Normal	4.00	1.5	6.3265	4.1016	5.1837
ψ	Normal	0.20	0.075	0.0572	0.1177	0.1014
$r_{\Delta\pi}$	Normal	0.30	0.10	0.1769	0.1511	0.1290
$r_{\Delta y}$	Normal	0.0625	0.05	0.1753	0.1485	0.1754
ρ	Beta	0.80	0.10	0.9293	0.9384	0.9307
r_π	Normal	1.70	0.10	1.4736	1.5281	1.4705
r_y	Normal	0.125	0.05	0.1221	0.1038	0.1038
σ_c	Normal	1.0	0.375	2.1640	2.2826	2.2265
σ_l	Normal	2.0	0.75	0.5000	0.5083	0.5480
ϕ	Normal	1.45	0.25	1.5815	1.7002	1.6953
ξ_w	Beta	0.75	0.05	0.5869	0.6001	0.5780
$\rho(\varepsilon_t^a)$	Beta	0.85	0.10	0.9570	0.9568	0.9574
$\rho(\varepsilon_t^b)$	Beta	0.85	0.10	0.2749	0.2719	0.2767
$\rho(\varepsilon_t^G)$	Beta	0.85	0.10	0.9776	0.9819	0.9786
$\rho(\varepsilon_t^I)$	Beta	0.85	0.10	0.6753	0.7180	0.7826
$\rho(\eta_t^Q)$	Beta	0.85	0.10	0.9762	0.9784	0.9777
$\sigma(\varepsilon_t^a)$	Inv gamma	0.40	2*	0.6236	0.6290	0.6259
$\sigma(\varepsilon_t^b)$	Inv gamma	0.20	2*	0.3078	0.3247	0.3201
$\sigma(\varepsilon_t^G)$	Inv gamma	0.30	2*	0.3472	0.3247	0.3509
$\sigma(\varepsilon_t^I)$	Inv gamma	0.10	2*	0.3111	0.3113	0.2688
$\sigma(\eta_t^Q)$	Inv gamma	0.40	2*	0.2331	0.2460	0.2401
$\sigma(\eta_t^R)$	Inv gamma	0.25	2*	0.2341	0.2209	0.2339
$\sigma(\eta_t^w)$	Inv gamma	0.10	2*	4.0755	4.1016	4.1457

Figure 4.6 Estimated Parameters Distribution of Taylor price setting



Chapter 5 Using an Indirect Inference Estimation Method to Estimate the Heterogeneous and Homogeneous Price Setting DSGE Models

5.1 Introduction

The different price-setting DSGE models were re-estimated in Chapter 4 by using seven main macro French economy data with the Bayesian estimation technique. Bayesian estimation maximises the marginal likelihood given the priors. The aim of the Bayesian estimation method is to find sets of structural parameters to look at how small the current period forecast error of the data is. An indirect inference is then applied based on these already estimated models in order to evaluate the performance of the models. In Chapter 3 the method of indirect inference is based on an already calibrated model, using the posterior mean of SW (2003); however, the testing results are not so strongly precise. The failure of the model to fit the data might be due to the model's misspecification. The model has failed with this set of calibrated values cannot infer that it will be rejected with another reasonable set of parameters. From this point of view, the failure of the price setting models in Chapter 3 may be due to the use of incorrect parameters to reflect the true structure of the economy. Consequently, the testing based on the Bayesian estimated models proceeded at the start of this chapter. The results show that all of these different price setting DSGE models are still strongly rejected.

In this chapter, indirect inference goes back to its original use as an estimation method to estimate the DSGE models and it is used to find out which model performs best based on the properly estimated models. The essence of indirect inference method is using an auxiliary model which is completely independent of the theory to generate data descriptors against the theoretical model is estimated or evaluated indirectly. To distinguish the indirect inference which is used in Chapter 3 as an evaluation method, the aim of indirect inference testing is to calculate the Wald statistics to see whether the estimates based on real data can be captured by the joint distribution based on the simulated data which is suggested by the theoretical model given the structural parameters were taken as given. Briefly speaking, the purpose of indirect inference testing is to see whether these two sets of estimates of the parameters of the auxiliary model are 'close enough'. On the contrary, indirect inference estimation is used in a different way, the aim is no longer to measure the 'distance' between the theory and the real data through using the auxiliary model but to find a set of parameters that minimizes such distance. The essence of estimation is to search a set of structural parameters over the whole range that can yield the real data based estimates are closest to the joint mean of these as model simulations would predict.

To distinguish the Bayesian estimation method that maximises the marginal likelihood given the priors which can be considered as a 'restrictions' or a 'belief', the indirect inference estimation technique maximises the marginal likelihood of the data behaviour based on the whole model over the whole range of possible parameter values in an 'unrestricted' way. The aim of indirect inference estimation is to find the best set of structural parameters to mimic the trajectory of the real data behaviour. This chapter aims to re-evaluate the competing models on their best possible versions according to the data. It will also be used as robustness check for the findings in the earlier chapters. The results show that after doing the estimation, the testing results improve considerably for all of the price-setting models since the calibrated values are set as an initial guess of the structural parameters and Simulated Annealing (hereafter SA) algorithms start these values and search for more appropriate sets of values to minimise the Wald statistics. The search process can be considered as the 'fine-tuning' of the calibrations. The indirect inference estimated results show that the ranking between different price settings is still unchanged. The GC and GTE price setting models still significantly less rejected compared with the conventional homogeneous price setting models.

In summary, although the model used in this chapter has many elements in common with that used in Smets and Wouters (2003), the analysis differs in two main aspects, which are: the introduction of heterogeneity price stickiness consistent with micro data, and the methodology for estimating the DSGE models. The heterogeneity of price stickiness introduced in the price setting equation are GTE and GC price settings, one measures the heterogeneity across different sectors in the economy and the other counts the heterogeneity across time span. Following the Indirect Inference estimation techniques that were developed by Gourieroux, Monfort et al.(1993), the different models are estimated by searching the best set of model parameters to minimise the Wald Statistics through using an independent auxiliary model, which is the essence of indirect inference. The purpose of the estimation in this chapter is twofold: firstly, it evaluates the abilities of the heterogeneity price stickiness of estimated New Keynesian DSGE model to capture the empirical stochastic and dynamics in the data; and secondly, the estimated model can be used to do a model comparison between the different price settings.

The rest of the chapter is structured as follows. Section 5.2 briefly presents the evaluation results based on Bayesian estimated models in Chapter 4. The indirect inference estimation methodology is discussed in Section 5.3. The estimation results are then shown in Section 5.4 and the model comparison based on these indirect inference estimated models is also analysed. Finally, Section 5.5 concludes this chapter.

5.2 Indirect Inference Evaluation Results Based on the Bayesian Estimated Models

All of these five different versions of the New Keynesian DSGE models have a common assumption in that they are characterised by optimising agents, capital accumulation, and monopolistic competition in both goods and labour markets, and nominal rigidities in prices and wages. In addition, they have the same estimated central bank interest rate policy. The interest rate rule has lagged interest rates, inflation, and output gap (which is defined as the difference between actual output and estimate of potential output). The difference between the models is the assumption of how agents set their prices. In the Calvo with indexation model the price setting follows a Calvo setup in which for every period the reset probability of price is random and the reset price is partially indexed by the observed lagged inflation rate. In the Generalised Calvo price setting model the reset price probability is no longer a constant. In the Generalised Taylor Economy price setting model the economy consists of many sectors, each of which has different fixed periods of contract.

In Chapter 3, the indirect inference evaluation is applied on the already calibrated models, the results report that all of these different price setting DSGE models are strongly rejected. The problem is that fixing the model parameters before evaluating and comparing these DSGE models is a strong assumption since the model's parameters could be taken to be any value in a reasonable range. In addition, the failure of the model to pass the test might due to the use of incorrect parameters to structure the 'true' economy. Consequently, the evaluation should be based on the estimated models in order to do a model comparison thoroughly. The main aim in Chapter 3 is to introduce this novel evaluation method. Thus, in this section, the same evaluation method (i.e. indirect inference) is used on these five already Bayesian-estimated models in order to make it more precise.

The structural shocks are re-calculated and the error processes are re-estimated with new autoregressive parameters based on the posterior means of Bayesian estimates of five different price setting models. The innovations' random components are then bootstrapped, drawing them as vectors to preserve any dependence between them. There are five endogenous variables (i.e. interest rate, output, consumption, investment and inflation) which are included in the auxiliary model VAR(1).

Table 5.1 summarise the evaluation results based on these different estimated models, which the only difference between these models is the price setting behaviour.

Table 5.1 Summary of the Test Results based on Bayesian estimated models

Models	***IC***	***GC***	***GTE***	***Calvo***	***Taylor***
Dynamics	100% (15.9646)	100% (7.2174)	100% (8.2390)	100% (13.7881)	100% (18.6969)
Volatilities	45.6% (-0.0399)	43.7% (-0.0459)	41.7% (-0.1144)	73.6% (0.1406)	70% (0.1386)
Full	100% (14.1885)	100% (6.7383)	100% (7.2094)	100% (10.0663)	100% (15.8156)

It can be seen in Table 5.1 that all of these different price settings in this DSGE framework are rejected. The Full Wald test statistic of 100% and the Normalised t-stats (which is reported in the parenthesis below the Wald stats) indicates that the data's dynamic properties are not close to that implied by the model. Although all of the models are rejected, the Normalised t-stats can be used to find which one is closer to the bound. The results indicate that the GC and GTE price setting models perform better than the conventional homogenous price setting models. Indexation scheme incorporated in the Calvo contract cannot better perform than simple Calvo contract. The 4-period simple Taylor performs worst among the five variants. The ranking of different price setting models is unchanged, which can also be considered as a robustness check of the results in Chapter 3.

5.3 Methodology

Indirect inference has been widely used in the estimation of structural models (Gregory and Smith 1991; Gourieroux, Monfort et al. 1993; Smith 1993). Indirect inference is a simulation-based method for estimating the parameters of economic models. It is most useful in estimating models for which the likelihood function is analytically intractable or too difficult to evaluate. Like other simulation-based methods, indirect inference requires only that it be possible to simulate data from the economic model for different values of its parameters. Unlike other simulation-based methods, the essence of this method is the use of an auxiliary model, which is a completely independent of the theory model, to capture aspects of the data which are then used to base the estimation on. The parameters of the auxiliary model can be estimated using either the observed data or data simulated from the economic model. The goal of indirect inference is to choose a set of parameters of the economic model so that these two estimates of the parameters of the auxiliary model are as close as possible. Wald statistics are used to measure the 'closeness' to see if the real-data-based estimates of the auxiliary model were captured by the joint distribution which is implied by the structural model.

There are a number of steps in indirect inference estimation. Firstly, given the initial values of the structural parameters[13], a random number generator is used to draw a sequence of random errors of the structural model to generate a number of pseudo samples of simulated data. The next step, which is based on the real data and simulated data, is to choose a metric for measuring the distance between the auxiliary model parameters, which is estimated using the observed data and the simulated data. In this chapter the Wald test is used as the metric to measure this distance. In the Wald approach, the indirect inference estimator of the parameters of the economic model minimises a quadratic form in the difference between the two vectors of estimated parameters:

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[13] The exercises use the calibrated values as in Table 2.1 as the initial input value of structural parameters for numerical iterations.

$$\theta = \min_{\theta}\left[\hat{\gamma}(\theta) - \gamma^{0}(\theta)\right]' \Sigma_{\gamma}^{-1}(\theta)\left[\hat{\gamma}(\theta) - \gamma^{0}(\theta)\right] \tag{5.1}$$

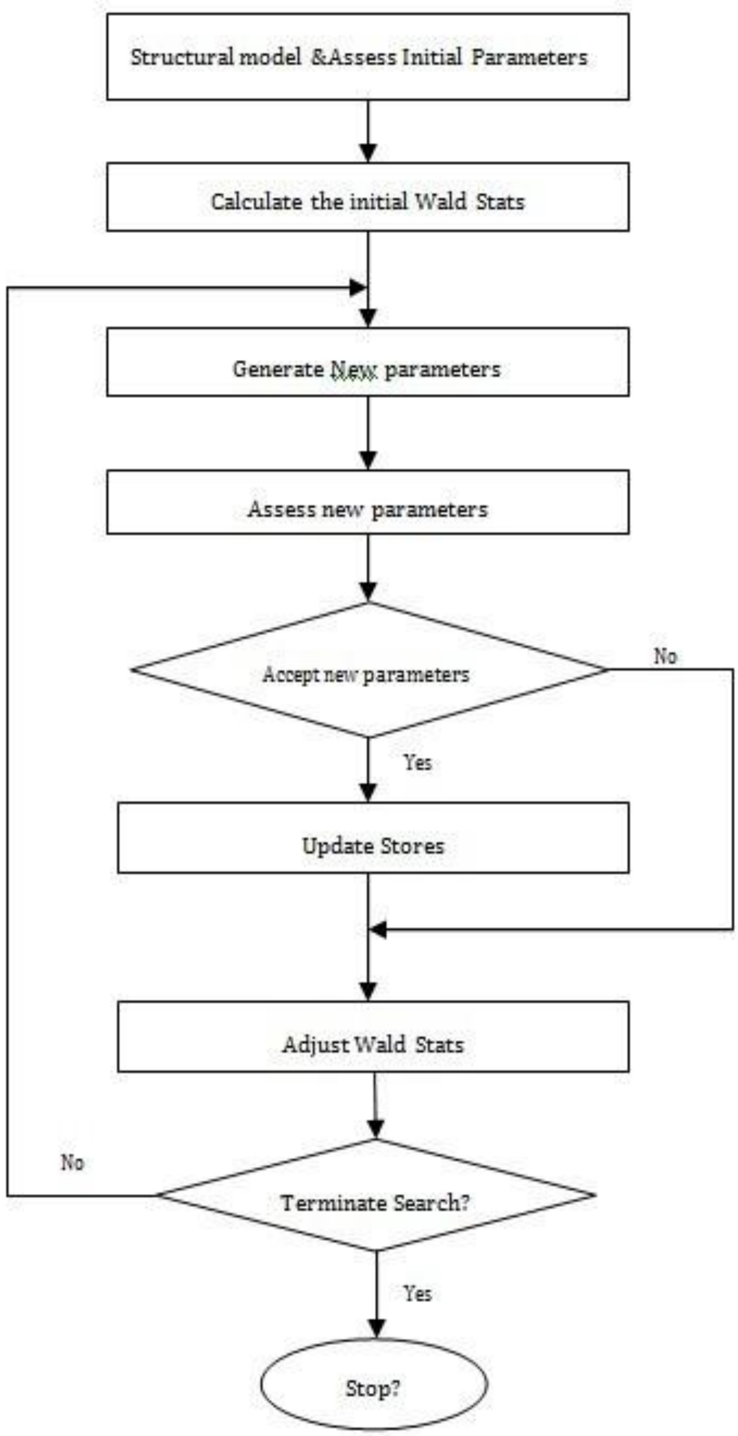
where the estimated parameter vector θ serves as a set of 'statistics' that capture, or summarise, certain features of the observed data and $\sum_{\gamma}^{-1}(\theta)$ is a positive definite weighting variance-covariance matrix of $\hat{\gamma}(\theta)$.

The covariance matrix can be obtained by bootstrapping the simulations. $\hat{\gamma}(\theta)$ is the vector of the VAR coefficients based on each simulated data with corresponding estimated parameter vector θ. $\gamma^{0}(\theta)$ is vector of the estimates' means based on the simulated data with corresponding estimated parameter vector θ. This minimised value of the metric can be used to test the hypothesis that the economic model is correctly specified. Another set of structural model parameter vectors θ_0 are then picked and iterated in the structural model, using the observed variables and the simulated random errors to generate another set of pseudo samples of simulated sequence of endogenous variables. The related Wald statistics can then be calculated. The steps to calculate Wald statistics are repeated by changing the value of structural coefficients until the calculated Wald statistics is minimised. As the observed sample size grows large, the estimated parameter vector in the simulated data converges to a so-called 'pseudo-true value' that depends on the structural model parameter θ, which explains why indirect inference generates consistent estimates of the parameters of the economic model.

So far there is no standardised notation or common software for use in this approach. The Simulated Annealing (SA) concept is introduced in order to imply the indirect inference estimation into practice. As its name implies, the simulated annealing exploits an analogy between the way in which a metal cools and freezes into a minimum energy crystalline structure and search for a minimum in a more general system. The metal cooling and freezes process in SA can be considered as the process of finding the minimum Wald statistics implied by the observable data and simulated data. In addition, the SA's major advantage over other methods is an ability to avoid becoming trapped at local minima.

At each step, the SA heuristic considers some neighbouring state s' of the current state s, and probabilistically decides between moving the system to state s' or staying in state s (the state s in an indirect inference estimation procedure can be considered as the set of structural parameters). These probabilities ultimately lead the system to move to states of lower energy (in indirect inference estimation, this is equivalent to lower Wald-Stats). Typically this step is repeated until the system reaches a state that is good enough for the application, or until a given computation budget has been exhausted. Figure 5.1 below briefly illustrates the whole SA working procedure.

Figure 5.1 Structure of the Simulated Annealing algorithm



5.4 Results

5.4.1 Parameter Estimation

In section 5.2 the evaluation results are based on parameter values that are estimated by using Bayesian method as in SW (2003), which finds the best set of parameters by maximising marginal likelihood given priors. Consequently, all of the models are rejected substantially. The indirect inference estimation is then introduced with the aim to make the testing results more accurate and robust from another point of view to estimate. Bayesian estimation method with aims to mimic the data in each time point, while indirect inference technique focuses on replicating the data behaviour by using auxiliary model VAR(1) to express the variables' correlation between current and lag periods. Table 5.2 contains the indirect inference estimation results for structure parameters of different price setting models.

Table 5.2 Summary of Indirect Inference Parameter Estimation Results

Parameter	*SW estimation*	*IC*	*GC*	*GTE*	*Calvo*	*Taylor*
γ_w	0.763	0.675	0.496	0.508	0.725	0.302
h	0.573	0.950	0.948	0.946	0.939	0.919
φ	6.711	5.197	4.032	4.988	4.919	7.519
ψ	0.169	0.280	0.213	0.232	0.229	0.325
$r_{\Delta\pi}$	0.140	0.182	0.384	0.226	0.278	0.148
$r_{\Delta y}$	0.159	0.145	0.171	0.137	0.135	0.199
ρ	0.961	0.852	0.887	0.958	0.747	0.839
r_π	1.684	1.335	1.833	1.608	1.702	1.799
r_y	0.099	0.190	0.078	0.083	0.170	0.185
σ_c	1.353	2.923	1.320	1.519	2.767	2.783
σ_l	2.400	2.153	2.194	2.549	2.445	2.900
ϕ	1.048	1.858	1.244	1.573	1.735	1.998
ξ_w	0.737	0.839	0.628	0.736	0.835	0.936

Table 5.2 shows that the estimated parameters based on these different price setting models are reasonably around the calibrated values. The estimated results show that the indexation parameter in the wage equation of all these price setting models is much lower than the value estimated by SW (2003) (0.763), which demonstrates that more forward looking of the Calvo wage contract dominates in all different price setting models. Whereas the survival rate in wage setting equation based on the homogeneous price setting models is higher than SW (2003) results (0.737), which indicates that the more rigid wage is required to fit the data in this price setting model. On the contrary, in GC and GTE price setting models a less wage rigid is found to better replicate the data behaviour than the other homogeneous price setting models.

Focusing on the habit persistence parameter h it can be seen that these different prices setting models yield quite similar high habit persistence value, which is almost one and half larger than SW (2003). The parameter to measure fixed cost ϕ in the production function is found to be a little bit higher in all price setting models than SW. The simple Taylor price setting model requires the highest fixed cost and the GC price setting model generate this parameter with the smallest value 1.244 among these different price setting models.

The other two parameters to measure the investment adjustment cost φ and capital utilisation cost ψ in different price setting models give quite different values. The 4-period Taylor price setting has the lowest investment adjustment cost (7.519) among five different price setting models. The estimates of capital utilisation cost in all of the different price setting models is higher than SW estimates (0.169), which implies a less capital utilisation cost and less persistence in capital accumulation.

Focusing on the parameters in the monetary policy functions, the parameter to governing interest rate smoothing pattern in SW estimates exhibits a fairly high inertia pattern. In the IC price setting model the interest rate is not as smooth as in the GTE and GC price setting models. The model suggests that the relative weight the monetary authority puts on output gap was almost doubled in the IC price setting model (0.19) than in GC and GTE price setting models. Yet the monetary authority's response to inflation in all these different price setting models was still essentially strong as in SW estimates. The elasticity of intertemporal consumption (inverse of σ_c) and that of labour (inverse of σ_l) in homogeneous price setting models were both slightly less than SW estimates, while GC and GTE price setting models generate similar values as in SW estimates.

It is expected that the estimated model will be less rejected than the calibrated ones because the starting point to let the SA algorithm search for the best set of structural parameters to fit the data implication are the calibrated values taken from SW (2003) Bayesian estimates. The SA algorithm searching process will terminate only when the Wald statistics cannot be any smaller and the set of parameters can be found from this.

5.4.2 Evaluating the SW model with Calvo with Indexation Price Setting

The structural shocks are re-calculated based on the estimates of structural parameters by using indirect inference method. Table 5.3 demonstrates that the evaluation based on the estimated model can fit the data better than calibrated ones because the Normalised t-stats is decreased considerably from the results in Chapter 3.

Table 5.3 Individual VAR Coeffs based on II estimated IC price setting

VAR Coeffs	***Actual Estimate***	***95% Lower Bound***	***95% Upper Bound***	***State***
A_R^R	0.879390	0.714389	0.954636	in
A_Y^R	0.004051	-0.133718	0.148783	in
A_C^R	-0.011138	-0.076667	0.108813	in
A_I^R	0.005509	-0.023914	0.037415	in
A_π^R	-0.007705	0.072621	0.250935	out
A_R^Y	-0.442315	-0.186182	0.365811	out
A_Y^Y	0.978999	0.588189	1.134624	in
A_C^Y	0.056980	-0.174257	0.207077	in
A_I^Y	0.021198	-0.040606	0.081201	in
A_π^Y	0.019380	-0.585925	-0.132868	out
A_R^C	-0.236674	-0.267093	-0.019420	in
A_Y^C	0.009694	-0.143854	0.127773	in
A_C^C	0.936638	0.802736	1.000012	in
A_I^C	-0.010419	-0.032074	0.029223	in
A_π^C	0.016716	-0.103876	0.121516	in
A_R^I	-1.279060	-0.416167	1.985888	out
A_Y^I	0.115378	-1.539146	0.961183	in
A_C^I	-0.009020	-0.770340	0.973312	in
A_I^I	0.923159	0.736308	1.279898	in
A_π^I	-0.050816	-2.651709	-0.571084	out
A_R^π	-0.033057	-0.250693	0.190735	in
A_Y^π	-0.010158	-0.337845	0.172995	in
A_C^π	0.021340	-0.193751	0.191262	in
A_I^π	0.012210	-0.044347	0.069952	in
A_π^π	0.935758	0.569058	0.963547	in
Wald Stats	100%	***Normalised t-stats***	4.6648	

According to Table 5.3, there are 5 out of the 25 real-data based estimates of the VAR coefficients that reflect the actual dynamics which are found to lie outside their corresponding 95% bounds that are implied by the theoretical model. Specifically, the response of the interest rate to inflation and the response of investment to inflation are both shown to be more passive than that predicted by the theoretical model. The response of investment to interest rate and the response of inflation to interest rate all lie outside of the model-simulated range. Overall, the Wald statistic is reported as 100%, which indicates that the model fails at the 95% confidence level, its normalised t-stats is 4.6648.

Turning to the other aspect of the concerned 'stylised facts', Table 5.4 below shows the extent to which the observed volatilities of real data are explained by the theoretical model:

Table 5.4 Volatilities of the Endogenous Variables based on II estimated IC price setting

Volatilities of the endogenous variables	*Values calculated with real data*	*95%Lower Bound*	*95%Upper Bound*	*State*
Var(R_t)	0.0026	0.0032	0.0678	out
Var(Y_t)	0.0530	0.0586	2.0768	out
Var(C_t)	0.0299	0.1462	0.2801	out
Var(I_t)	0.4057	1.1823	32.4446	out
Var(π_t)	0.0078	0.0067	0.0104	in
Directed Wald Statistics(for volatilities)	44.6%	***Normalised t-stats***	-0.0363	

As Table 5.4 shows that unlike the directed Wald test for volatility of the data shown in Chapter 3 that all five endogenous variables are individually out of the 95% model's implied bounds. This improves a little in this indirect inference estimated model version, at least inflation falls in the 95% bounds implied by the structural model, although the estimated model still produces generally excess variance of interest rate and too much excessive variances of output, consumption, and investment.

To evaluate the model's overall fitness to the real world, the results are reported in Table 5.5. The Wald Statistics is 99.8% and, therefore, the null hypothesis that the theoretical model is true is still rejected at 95% confidence level.

Table 5.5 Full Wald Statistics for II estimated IC price setting

	Full Wald Statistics	***Normalised t-stats***
Dynamics and Volatilities	99.8%	4.1808

5.4.3 Evaluating the SW Model with Generalised Calvo Price Setting

Table 5.6 below shows the testing results based on the estimated GC price setting model by using indirect inference technique. In the GC price setting model, there is only one out of twenty-five VAR individual coefficients lie outside the 95% range derived from the simulated data. Except the response of investment to inflation shows the passive pattern in the data compared with the simulated bound, all dynamic relationships shown by the real data are individually captured by the simulated 95% bounds. The overall Wald-stats are 99.5%, and the corresponding normalised t-stats equals to 2.8923, which is still lower than the IC price setting model. When compared with the evaluation results based on the calibrated version it can be seen that this is a significant improvement from 7.7207 to 2.8923.

Table 5.6 Individual VAR Coeffs based on II estimated GC price setting

VAR Coeffs	*Actual Estimate*	*95%Lower Bound*	*95%Upper Bound*	*State*
A_R^R	0.879390	0.526931	0.933454	in
A_Y^R	0.004051	-0.185952	0.087441	in
A_C^R	-0.011138	-0.050950	0.112969	in
A_I^R	0.005509	-0.018694	0.047850	in
A_π^R	-0.007705	-0.011615	0.102536	in
A_R^Y	-0.442315	-1.916689	-0.100320	in
A_Y^Y	0.978999	0.417952	1.449233	in
A_C^Y	0.056980	-0.325613	0.339289	in
A_I^Y	0.021198	-0.105789	0.152880	in
A_π^Y	0.019380	-0.299308	0.251334	in
A_R^C	-0.236674	-3.169380	0.078965	in
A_Y^C	0.009694	-0.824415	0.905603	in
A_C^C	0.936638	0.352261	1.462319	in
A_I^C	-0.010419	-0.213956	0.221410	in
A_π^C	0.016716	-0.275897	0.741429	in
A_R^I	-1.279060	-2.195808	1.134768	in
A_Y^I	0.115378	-1.259260	0.816265	in
A_C^I	-0.009020	-0.535768	0.845697	in
A_I^I	0.923159	0.792900	1.309298	in
A_π^I	-0.050816	-1.258830	-0.240623	out
A_R^π	-0.033057	-0.953986	0.304408	in
A_Y^π	-0.010158	-0.777929	0.070464	in
A_C^π	0.021340	-0.042315	0.515265	in
A_I^π	0.012210	-0.018536	0.190169	in
A_π^π	0.935758	0.692403	1.020418	in
Wald Stats	99.5%	***Normalised t-stats***	2.8923	

Yet the model can still explain the volatilities of the main endogenous variables, as shown in Table 5.7. Although the simulated data based on the theoretical model generates too much excessive variance in investment, it can fit the data of the other four variables quite well. The Wald Statistics for the volatilities part is 58.7%.

Table 5.7 Volatilities of the Endogenous Variables based on II estimated GC price setting

Volatilities of the endogenous variables	*Values calculated with real data*	*95%Lower Bound*	*95%Upper Bound*	*State*
Var(R_t)	0.0026	0.0026	0.0256	in
Var(Y_t)	0.0530	0.00415	0.2257	in
Var(C_t)	0.0299	0.0299	1.2871	in
Var(I_t)	0.4057	0.8889	29.9492	out
Var(π_t)	0.0078	0.00305	0.0292	in
Directed Wald Statistics(for volatilities)	58.7%	*Normalised t-stats*	0.0339	

The directed Wald Statistics based on the full consideration of dynamics and volatility is 99.4% which is reported in Table 5.8, which means that the theoretical model cannot generate the joint distribution of both dynamics and volatilities that simultaneously explains the ones observed in reality.

Table 5.8 Full Wald Statistics for II estimated GC price setting

	Full Wald Statistics	*Normalised t-stats*
Dynamics + Volatilities	99.4%	2.9211

5.4.4 Evaluating the SW Model with Generalised Taylor Economy Price Setting

Table 5.9 below gives the results based on the indirect inference estimated GTE price setting model. Compared with the results in calibrated model, the Normalised t-stats is much smaller and the Wald Statistics is 99.6%. It summarises how the actual dynamics are explained by the theoretical GTE price setting model. There is only one out of twenty-five VAR individual coefficients lie outside the 95% range derived from the simulated data. Except the response of consumption to interest rate shows the passive pattern in the data compared with the simulated bound, all dynamic relationships shown by the real data are individually captured by the simulated 95%

bounds. From the individual regressors' aspects, the GTE price setting model as well as GC price setting model performs best among these different price-setting models. The overall Wald Statistics are 99.6%, and the corresponding normalised t-stats is equal to 3.2848.

Table 5.9 Individual VAR Coeffs based on II estimated GTE price setting

VAR Coeffs	***Actual Estimate***	***95%Lower Bound***	***95%Upper Bound***	***State***
A_R^R	0.879390	0.340646	0.992948	in
A_Y^R	0.004051	-0.163538	0.057611	in
A_C^R	-0.011138	-0.031809	0.090991	in
A_I^R	0.005509	-0.009368	0.043301	in
A_π^R	-0.007705	-0.034199	0.226005	in
A_R^Y	-0.442315	-3.148900	-0.266755	in
A_Y^Y	0.978999	0.204459	1.161442	in
A_C^Y	0.056980	-0.138923	0.381658	in
A_I^Y	0.021198	-0.025335	0.203123	in
A_π^Y	0.019380	-0.277085	0.932518	in
A_R^C	-0.236674	-4.949344	-0.385948	out
A_Y^C	0.009694	-0.879256	0.387710	in
A_C^C	0.936638	0.654472	1.403707	in
A_I^C	-0.010419	-0.077982	0.239011	in
A_π^C	0.016716	-0.134131	1.804125	in
A_R^I	-1.279060	-4.448846	1.918516	in
A_Y^I	0.115378	-1.618828	0.639157	in
A_C^I	-0.009020	-0.422142	1.018279	in
A_I^I	0.923159	0.853396	1.385241	in
A_π^I	-0.050816	-1.881528	0.771295	in
A_R^π	-0.033057	-1.023787	0.432847	in
A_Y^π	-0.010158	-0.342671	0.169635	in
A_C^π	0.021340	-0.090353	0.226927	in
A_I^π	0.012210	-0.032665	0.087510	in
A_π^π	0.935758	0.654437	1.322130	in
Wald Stats	99.6%	***Normalised t-stats***	3.2848	

Turning to the volatilities of the endogenous variables, Table 5.10 shows that the theoretical model has difficulties mimicking the performance of investment, which generates too much variance (as in the previous two models). The Wald Statistics is reported as 64.5%, which implies that the model can jointly explain the observed volatilities in a proper way.

Table 5.10 Volatilities of the Endogenous Variables based on II estimated GTE price setting

Volatilities of the endogenous variables	*Values calculated with real data*	*95%Lower Bound*	*95%Upper Bound*	*State*
Var(R_t)	0.0026	0.0024	0.0249	in
Var(Y_t)	0.0530	0.0437	2.1084	in
Var(C_t)	0.0299	0.0298	1.2112	in
Var(I_t)	0.4057	0.9599	29.6116	out
Var(π_t)	0.0078	0.0031	0.0260	in
Directed Wald Statistics(for volatility)	64.5%	***Normalised t-stats***	0.0847	

Table 5.11 reports the overall performance of the model. The GTE price setting model is still rejected at an even more tolerant 99% confidence level with a little higher M-metric value than GC which is still lower than IC price setting model.

Table 5.11 Full Wald Statistics of II estimated GTE price setting

	Full Wald Statistics	*Normalised t-stats*
Dynamics and Volatilities	99.6%	3.2729

5.4.5 Evaluating the SW Model with Calvo Price Setting

Table 5.12 demonstrates that the evaluation results based on the estimated model can fit the data better than the calibrated ones. The Normalised t-stats have decreased considerably when compared with the results in Chapter 3.

Table 5.12 Individual VAR Coeffs based on II estimated Calvo price setting

VAR Coeffs	***Actual Estimate***	***95% Lower Bound***	***95% Upper Bound***	***State***
A_R^R	0.879390	0.7114	0.9525	in
A_Y^R	0.004051	-0.1391	0.1499	in
A_C^R	-0.011138	-0.0791	0.1123	in
A_I^R	0.005509	-0.0242	0.0384	in
A_π^R	-0.007705	0.0766	0.2568	out
A_R^Y	-0.442315	-0.1741	0.3678	out
A_Y^Y	0.978999	0.5830	1.1216	in
A_C^Y	0.056980	-0.1677	0.2102	in
A_I^Y	0.021198	-0.0397	0.0820	in
A_π^Y	0.019380	-0.6024	-0.1447	in
A_R^C	-0.236674	-0.2661	-0.0205	in
A_Y^C	0.009694	-0.1418	0.1279	in
A_C^C	0.936638	0.8009	1.0000	in
A_I^C	-0.010419	-0.0316	0.0288	in
A_π^C	0.016716	-0.1030	0.1207	in
A_R^I	-1.279060	-0.4048	1.9877	out
A_Y^I	0.115378	-1.5772	0.9413	in
A_C^I	-0.009020	-0.7571	0.9778	in
A_I^I	0.923159	0.7480	1.2795	in
A_π^I	-0.050816	-2.7399	-0.6300	out
A_R^π	-0.033057	-0.2807	0.1471	in
A_Y^π	-0.010158	-0.3102	0.1515	in
A_C^π	0.021340	-0.1794	0.1742	in
A_I^π	0.012210	-0.0375	0.0669	in
A_π^π	0.935758	0.5824	0.9412	in
Wald Stats	100%	***Normalised t-stats***	4.5907	

It can be seen from Table 5.12 that there are 4 out of the 25 real-data based estimates of the VAR coefficients that reflect the actual dynamics are found to lie outside of the corresponding 95% bounds which are implied by the theoretical model. Specifically, the response of interest rate to inflation and the response of investment to inflation are both shown to be more passive than that which the theoretical model could predict. Overall, the Wald statistic is reported as 100%, which indicates that the model fails at 95% confidence level and its Normalised t-stats is 4.5907.

Table 5.13 below shows how the observed volatilities of real data are explained by the theoretical model.

Table 5.13 Volatilities of the Endogenous Variables based on Calvo price setting

Volatilities of the endogenous variables	***Values calculated with real data***	***95%Lower Bound***	***95%Upper Bound***	***State***
Var(R_t)	0.0026	0.0054	0.0675	out
Var(Y_t)	0.0530	0.0581	2.0680	out
Var(C_t)	0.0299	0.0146	0.2797	out
Var(I_t)	0.4057	1.1730	33.0923	out
Var(π_t)	0.0078	0.0067	0.1045	in
Directed Wald Statistics(for volatilities)	45.1%	***Normalised t-stats***	-0.0351	

Table 5.13 shows that although the estimated model still produces generally excess variance of interest rate and excessive variances of output, consumption, and investment, this improves a little on the estimated model version (at least inflation falls in the 95% bounds as implied by the structural model). However, jointly, the directed Wald statistics is 45.1%, which clearly passes the test.

Table 5.14 Full Wald Statistics for II estimated Calvo price setting

	Full Wald Statistics	***Normalised t-stats***
Dynamics + Volatilities	99.8%	4.0812

Table 5.14 reports the model's overall fitness to the real world, the Wald Statistics is 99.8%. Hence the null hypothesis that the theoretical model with Calvo type price setting is true is still rejected at 95% confidence level.

5.4.6 Evaluating the SW Model with Taylor Price Setting

Table 5.15 shows the dynamics results based on the 4-period Taylor type price setting model. There is 4 out of 25 VAR coefficients lie outside the 95% simulated bound. The responses of output to interest rate and also to inflation are both outside the simulated bound. The response of investment to inflation and also to output are both less aggressive than the model stimulated 95% upper and lower bound. Overall, the Wald statistic is reported as 100%, which indicates that the model fails at 95% confidence level, its Normalised t-stats is 8.2845.

Table 5.15 Individual VAR Coeffs based on II estimated Taylor price setting

VAR coeffs	***Actual Estimate***	***95%Lower Bound***	***95%Upper Bound***	***State***
A_R^R	0.879390	0.7430	1.0222	in
A_Y^R	0.004051	-0.0948	0.0624	in
A_C^R	-0.011138	-0.0395	0.0689	in
A_I^R	0.005509	-0.0122	0.0258	in
A_π^R	-0.007705	-0.0963	0.0700	in
A_R^Y	-0.442315	-0.3180	0.6130	out
A_Y^Y	0.978999	0.6583	1.1685	in
A_C^Y	0.056980	-0.1391	0.2033	in
A_I^Y	0.021198	-0.0526	0.0724	in
A_π^Y	0.019380	-0.7095	-0.1198	out
A_R^C	-0.236674	-0.6438	-0.1722	in
A_Y^C	0.009694	-0.1310	0.1635	in
A_C^C	0.936638	0.8196	1.0249	in
A_I^C	-0.010419	-0.0362	0.0367	in
A_π^C	0.016716	-0.0963	0.2257	in
A_R^I	-1.279060	-0.3966	4.0141	out
A_Y^I	0.115378	-1.1787	1.1676	in
A_C^I	-0.009020	-0.7894	0.9028	in
A_I^I	0.923159	0.6361	1.2368	in
A_π^I	-0.050816	-3.4105	-0.5429	out
A_R^π	-0.033057	-0.3817	0.2111	in
A_Y^π	-0.010158	-0.2430	0.1820	in
A_C^π	0.021340	-0.1473	0.1557	in
A_I^π	0.012210	-0.0438	0.0632	in
A_π^π	0.935758	0.5807	0.9506	in
Wald Stats	100%	***Normalised t-stats***	4.6745	

Turning to the other aspect of the volatilities of the endogenous variables, Table 5.16 below shows the extent to which the observed volatilities of real data are explained by the theoretical model:

Table 5.16 Volatilities of the Endogenous Variables based on II estimated Taylor price setting

Volatilities of the endogenous variables	***Values calculated with real data***	***95%Lower Bound***	***95%Upper Bound***	***State***
Var(R_t)	0.0026	0.0366	0.1746	out
Var(Y_t)	0.0530	0.2150	3.5383	out
Var(C_t)	0.0299	0.4085	2.3749	out
Var(I_t)	0.4057	0.9987	22.4106	out
Var(π_t)	0.0078	0.0082	0.0903	out
Directed Wald Statistics(for volatilities)	89.3%	***Normalised t-stats***	0.9481	

Table 5.16 shows that all of the five endogenous variables are individually outside of the 95% model-implied bounds. Although all variables are individually outside the model-simulated range, jointly they still pass the test at a 5% significance level.

Table 5.17 reports the model's overall fitness to the real world, the Wald Statistic is 100%. The null hypothesis that the theoretical 4-period simple Taylor model is true is still rejected at a 95% confidence level.

Table 5.17 Full Wald Statistics for II estimated Taylor price setting

	Full Wald Statistics	***Normalised t-stats***
Dynamics and Volatilities	99.9%	4.2095

Table 5.18 summarise the evaluation results of the different price setting models based on the indirect inference estimation results, which the only difference between these models is the price setting. The results show GC and GTE price setting models are still superior to the homogeneous price setting models even after the models are properly estimated, which means this type heterogeneity in price stickiness can empirically better explain the macro data in the French economy.

Table 5.18 Summary of the Test Results based on Indirect Inference Estimation Results

Models	***IC***	***GC***	***GTE***	***Calvo***	***Taylor***
Dynamics	100% (4.6648)	99.5% (2.8923)	99.6% (3.2848)	100% (4.5907)	100% (4.6745)
Volatilities	44.6% (-0.0363)	58.7% (0.0339)	64.5% (0.0847)	45.1% (-0.0351)	89.3% (0.9481)
Full	99.8% (4.1808)	99.4% (2.9211)	99.6% (3.2729)	99.8% (4.0812)	99.8% (4.2095)

In summary, the overall performance of heterogeneous price setting models is better than the homogeneous price setting models, which can be directly seen from the Wald statistics and the corresponding Normalised t-stats. Focusing on the model's ability to fit the empirical dynamics of the economy, homogeneous price setting models have failed to explain the several aspects of the transmission mechanism such as the transmission of interest rate shock to output. Turning to the volatility part, homogeneous price setting models generate too much variance of main macro variables while simulated data generated from heterogeneous price setting models can match the real data properly.

5.4.7 A Comparison of the Different Variable Combinations of Different Price Settings

When the five variables are considered into the auxiliary model VAR(1), all of different price setting models are rejected. This happens in both the calibrated model and also estimated model by using different estimation methods. This rejection might due to the incapability of these models to measure consumption and investment. From the point of view of the key variables that policymakers are most focused on (i.e. interest rate, inflation and output), the GC and GTE price setting models can successfully pass the test and the IC price setting model can also pass the test in a more tolerant way at a 99% confidence level. Table 5.19 reports the Wald Statistics by different variable combinations.

Table 5.19 Directed Wald statistic by Variable Combinations

Variable combinations	*IC*	*GC*	*GTE*	*Calvo*	*Taylor*
R,Y,π	98.3% (2.8756)	88.8% (1.0578)	94% (1.5253)	98.1% (2.4390)	99.5% (3.6334)
Y,π	97.2% (2.0641)	88.3% (1.0027)	90.5% (1.2145)	97% (2.0466)	98.7% (3.1904)
R,π	97.4% (2.3828)	57.4% (0.2827)	56.5% (0.1808)	95.4% (1.6987)	80.3% (0.7374)
R	81.6% (0.2401)	90% (0.8534)	78.2% (0.1776)	92.2% (1.2045)	87.4% (0.8431)
Y	72.8% (-0.0255)	62.2% (-0.1221)	65.6% (-0.0883)	80.1% (0.1913)	81.3% (0.2199)
π	80.7% (0.3613)	70.4% (0.2648)	46.2% (-0.1110)	92.1% (1.1075)	93.3% (1.1962)

The results are found to have considerably improved after the indirect inference estimation is applied on these different price setting models. Turning to the different variables combination (which only focuses on inflation, output and interest rate) it can be seen that all these five models do a better job. GTE and GC have clearly passed the test at 95% confidence level while the conventional homogenous price setting models have marginally passed the test at a more tolerant 99% confidence level. As the robustness check as the IRFs and mean lag which are shown in Chapter 2, GC can fit the output better while GTE can capture the inflation dynamics better.

5.5 Conclusion

By using an indirect inference technique, this chapter extends the comparison of different price setting models based on calibrated values to a more precise and reasonable comparison based on the proper estimated models. The indirect inference estimation method maximises the likelihood function of the data behaviour conditional on the whole model over the whole range of the possible parameter values. ‘Indirect’ means that it uses an auxiliary model. This thesis uses the VAR(1) as the auxiliary model to measure the data behaviour. Since there is no uniform way to do this estimation, the Simulated Annealing algorithm is introduced with the aim to find the best set of structural parameters to minimise the Wald Statistics. The advantage of using a Simulated Annealing algorithm to do the indirect inference estimation is that it can find the global minimum.

The evaluation results of the performance of these indirect inference estimated price setting models are all improved significantly when compared with the calibrated versions, although the ranking of these price setting models are unchanged. GC and also GTE price setting models are found to be overwhelmingly superior to the conventional homogeneous price setting models. These evaluation results based on the indirect inference estimated models also confirm the results of the Bayesian estimation that the GC price setting model yields the best value in terms of marginal likelihood. Although the two estimation methods use quite different criterion to find the ‘best’ parameters to fit the data and data behaviour respectively, all of the results show that GC price setting in the context of DSGE model is the only model which can clearly fit the data behaviour of the French economy.

Chapter 6 Overall Conclusion

This thesis investigates the different types of price rigidities in the context of a DSGE model of the French Economy. Time-dependent price setting rules are the focus of this thesis. Two main categories of price setting are considered under this dimension. One is the conventional homogeneous price setting rules (simple Calvo, simple Taylor, and Calvo with Indexation), while the other is the heterogeneous price setting rules (GTE and GC) which directly emerges the micro data evidence (Baudry, Le Bihan et al. 2007; Dixon and Le Bihan 2010) into macro DGSE model consideration. In the GTE, there can be multiple sectors with differentiated price durations, where in each sector there is a simple Taylor pricing strategy. the simple Taylor pricing rule can be considered as a special case of GTE when there is only sector in the economy, Whereas in the GC, there price reset are duration dependent. The longer the price has been the higher probability that it will be renewed. Both of these heterogeneous price stickiness models are consistent with same steady state distribution of price duration. Using the unified framework of Dixon (2010), the estimated hazard function of the distribution of price-spell durations in the data can infer a unique one-to-one cross-sectional distribution under the assumption of a steady state. However, although they share the exactly the same steady state distribution of durations, the essence of these two heterogeneous price setting models differs. Specifically, in GTE price setting, firms know exactly how long their price will last ex ante while GC price setting model is firms must look ahead into the distant future when they set prices. Thus, GC price setting is more forward looking than GTE.

Based on the main context of the SW (2003) model, the heterogeneous price setting rules (Wolman 1999; Dixon and Le Bihan 2010) are introduced into the macro DSGE framework. The results from the numerical simulation for the full models with different price contracts show that heterogeneous price setting rules are more capable of generating inflation inertia and output persistence than homogeneous price setting strategies. Specifically, from the impulse response of output and inflation from a monetary policy shock and the associated measure of mean lag, GC price setting model can generate longer output persistence while GTE can capture the longer inflation persistence effect. Besides that, GTE is the only model can match the empirical feature that the inflation dynamics is delayed after the output. In addition, a smoothness pattern in consumption and interest rate can be found in model based impulse response functions. Incorporation of heterogeneity in price stickiness amplifies the 'contract multiplier' effect that the more rigid sectors have a disproportionate effect on the aggregate price level which in turn influences the less rigid sectors to change price infrequently. Therefore, these interactions between different sectors make the heterogeneity in price stickiness to affect aggregate dynamics in quantitatively important ways. Because of lacking of enough micro price evidence, there is only longest 23 months price contracts are taken into consideration, investigating more micro price data evidence as well as micro wage data to model heterogeneous wage stickiness are future research area. Moreover, there are various real rigidities incorporated into the SW (2003) DGSE models, excluding these real frictions (i.e. habit formation in consumption) in the model can give a more clear view to analyse how price (or wage) rigidity can help to capture the model to matching the empirical facts.

Various macroeconometric methods are then applied in order to do model estimation and comparison. A new bootstrap method 'indirect inference', which was developed by Minford et.al (2007), is applied to measure the model's overall capacity to fitting the data behaviour. The essence of this method is the separation between the theoretical model as the null hypothesis and using the independent auxiliary model such as VAR as the data descriptors. It begins with the calibrated value of structural parameters in all different price setting models. On the main test criterion, the Wald Statistics based on the VAR parameters and volatilities of main macro variables, the testing results show that the different price stickiness setups in this NNS framework are all comprehensively rejected. The advantages of indirect inference testing method is that it provides a way to test whether the model is true or not in an absolute way by using Wald statistics. In particular, although all five price setting model failed to pass the test, to rank the performance of different models, GC is the best one and GTE is the second best. In particular, the GTE price setting model is also the only model can capture inflation and output persistence, also the transmission mechanism of interest rate. Besides that, the ad hoc indexation scheme in Calvo model cannot perform better than simple Calvo model which indicate that it is better to exclude this friction out. When the focus is placed on the main macro variables (i.e. interest rate, inflation and output), the GC price setting model is found to perform best and the GTE comes second. It is, therefore, proven that heterogeneous price setting rules can considerably improve the performance of DSGE models.

A Bayesian estimation method is then applied to estimate the structural parameters by using both macro data and micro data evidence (Dixon and Le Bihan 2010) of the French economy. The structural parameters are shown to be different from those found in SW (2003) for the Euro area. In particular, more habit persistence, more fixed cost in production function, less capital adjustment cost, investment adjustment cost, and less wage rigidity are shown in the results compared with SW (2003). The elasticity of labour supply is not pinned down very precisely by the data. One of most important advantages of Bayesian approach is that it provides a way to find the most useful model with least overall misspecification, which can be done with a marginal likelihood of the model. The marginal likelihood of a model is directly related to the predictive density function. The predictive performance is the natural criterion for validating models for forecasting and policy analysis.

A Bayes factor is used to measure the relative usefulness of different price setting models. The results strongly favour GC price settings. The GTE price setting model does not perform better than simple Calvo due to the lack of longer price contracts being taken into consideration. In homogeneous price setting models a simple Taylor price setting model performs worst and partial lagged indexation scheme in Calvo type contract cannot improve the performance of DSGE models. Different priors and also different observables are also used for the robustness check. However, the ranking of different price setting models are still not changed. In this chapter, the sectoral price stickiness and duration dependent hazard rate in heterogeneous price modelling is fixed as the evidence from the micro data. In future research, the micro price and also wage evidence can be used as priors. The parameters to governing sectoral price and wage (also duration dependent hazard rate) can be estimated by using Bayesian techniques.

Indirect inference evaluation in Chapter 2 is based on the calibration models, all of the models fail to pass the test. One possibility is due to the model misspecification, the other possible reason is due to the inappropriate calibrated values of structure parameters of the models. Although Chapter 4 reports the relative ranking of different price setting models, whether or not the model itself can reflect the true structure of the economy cannot be known from the results. Thus, based on these two points of view, indirect inference evaluations are conducted on these properly estimated models. Bayesian estimated models still cannot pass the indirect inference testing successfully. Finally, the indirect inference estimation method is conducted to estimate the structural parameters and evaluate the model's performances to fit the data behaviour. The purpose of this step is to re-evaluate the competing models on their best possible versions according to the data. It expects that the estimated version based on indirect inference will perform no worse than calibrated version. Since the calibrated values are set as initial guess for the structural parameters, the SA algorithm will start searching from these values and replace them with more appropriate ones whenever a smaller Wald statistics can be found, which can be treated as a 'fine-tuning' process. The results can also be used as an effectively robust check of the earlier findings in the previous chapters.

Compared with the Bayesian estimation technique, the advantage of indirect inference estimation method is the 'unrestricted way' that it uses the whole range to get the set of structural parameters yielding the global minimum of 'Wald statistics', although indirect inference estimation cannot figure out the problems of unavailable data of omitted variables and also have the identification problem in the first step to calculate structural shocks. The testing results are improved on all five price setting models even though the ranking of models' performance is still unchanged. The indirect inference estimated model is less rejected and more precise from the data's point of view. Different combinations of variables have also been tried, in particular, when only focusing on the main macro variables (i.e. output, interest rate and inflation), GC and GTE price setting models can easily pass the test at 95% confidence level while other homogeneous price setting models can also pass the test at 99% confidence level.

Although in this thesis, two different econometric methods which are used to estimate and evaluate different price setting models have quite different criterion to find the 'best' set of structural parameters to fit the data (Bayesian technique) and data behaviour (indirect inference approach), all of the results show that heterogeneous price setting models can improve the model's performance significantly than homogeneous alternatives. This improvement greatly enhances the empirical validity and reliability of using the heterogeneous price setting models and also can be used for optimal monetary policy and welfare analysis.

Overall, the heterogeneous price setting strategies can significantly improve the explanatory power and prediction precision of DSGE models. It not only combines the micro data evidence directly into the macro DSGE model to overcome the shortcomings of an ad hoc indexation scheme which does not have a proper micro foundation, but it also surmounts the problem of simple Calvo and Taylor contracts which cannot mimic the complicated real world. In addition, it solves the important puzzle between the high degree of nominal rigidity and extent of persistence under homogeneous price setting models. Although different estimation and evaluation procedures give different points of emphasis to view the data and model implications, the GC price setting model is proven to fit either the data or the data behaviour best as a whole while GTE price setting model can better fit the dynamics of inflation and output as well as the co-movement of inflation and output.

To including more sectors (longer contracts) into price setting model can help to improve model's ability to match the empirical features of the economy. In this thesis the wage setting behaviour remains the same as in SW (2003) (which follows the Calvo with indexation scheme) due to the unavailability of micro wage data. In future work, it is interesting that GC and GTE wage setting rules be introduced into the DSGE framework to try to figure out the importance of wage setting behaviour to improve the model's overall performance. Besides that, to change the structure of economy modelled in SW (2003) and CEE (2005) in some way in addition to the pricing part is also interest of future research. Excluding the habit formation in consumption, introducing firm-specific capital or labour remain for future work.

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